ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

A TAILORED HYBRID RISK ASSESSMENT MODEL FOR COASTAL FLOW SLIDES ALONG WITH MANAGEMENT STRATEGIES

Ph.D. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

YÖNETİM STRATEJİLERİ İLE BİRLİKTE KIYI HEYELANI İÇİN UYARLANMIŞ BİR HİBRİT RİSK DEĞERLENDİRME MODELİ

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Ahmet DURAP, a Ph.D. student of İTU Graduate School student ID 517182001, successfully defended the thesis/dissertation entitled "A TAILORED HYBRID RISK ASSESSMENT MODEL FOR COASTAL FLOW SLIDES ALONG WITH MANAGEMENT STRATEGIES", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To the cherished women in my life, my dearest mom, beloved sisters, and those who have made a difference in my life,

FOREWORD

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In this journey, I have been blessed with the unwavering love and support of the cherished women in my life: my dearest mom, beloved sisters, and dear ones. Their constant encouragement and belief in me have been my greatest source of strength.

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With sincere appreciation,

January 2024

Ahmet DURAP
(M.Sc.Coastal&Civil Engineer)

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ABBREVIATIONS

APBS	: Amity Pint Beach Sand
BN	: Bayesian Network
CFS	: Coastal Flow Slide
CS	: Coarse Sand
CRBF	: Coastal Retrogressive Breaching Failure
DSI	: Durap Sensitivity Index
ES	: Experimental Study
HMS	: Heavy Mineral Sand
HRM	: Hybrid Risk Model
HTL	: High Tide Level
LFS	: Liquefaction Flow Slide
LTL	: Low Tide Level
MS	: Medium Sand
SI	: Site Inspection
SID	: Sensitivity Index Development
SWH	: Significant Wave Height

SYMBOLS

n : The total number of observations

Y_i : The actual value

$\hat{Y}_i$: The predicted value

$\bar{Y}$: The mean of the actual values

φ : Internal friction angle of a soil

δ : Horizontal displacement

h : Height of the specimen

K : Hydraulic conductivity

Q : Flow rate

h_1 : Height of water in the first tube plus height difference

h_2 : Height of the water column in the bottom tube

L : Sample height

k_L : Liquefaction flow slide coefficient

k_{BF} : Breaching flow slide coefficient

k_L : Liquefaction flow slide coefficient

$P(V_{liquefaction})$: The probability of liquefaction

$P(V_{breach})$: The probability of breaching

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A TAILORED HYBRID RISK ASSESSMENT MODEL FOR COASTAL FLOW SLIDES ALONG WITH MANAGEMENT STRATEGIES

SUMMARY

Coastal flow slide (CFS) is a type of landslide that occurs in coastal areas, where a mass of soil and rock flows downhill. It can be divided into two categories: breaching and liquefaction, which have different mechanisms and sand movement dynamics, but both lead to the same result: a large mass of sand and other materials flowing downslope.

Breaching, coastal retrogressive breaching flow slides (CRBF), the first type of coastal flow slide, happens in densely packed sand. It starts when the sand grains dilate, or spread apart, which creates negative pore pressure. This causes the sand grains to flow downhill one by one, in a gradual process.

Liquefaction flow slides (LFS), on the other hand, is a more abrupt process because the sand suddenly loses its strength and flows like a liquid.

Although this topic has been discussed in the literature, there are only a few studies on it. One of the biggest challenges in CFS is that these hazards often start below the water surface. This makes them difficult to identify and study in detail. The complexity of underwater conditions also makes it difficult to analyze these hazards, and the lack of knowledge on this topic also indicates a significant gap in risk management.

Given the challenges of studying coastal flow slides, it is clear that new and innovative approaches are needed. This study introduces a novel sensitivity index and a sophisticated hybrid model that can be used to gauge the risk of coastal flow slides and identify vulnerable coastal regions. The hybrid model comprises five distinct components:

Bayesian Network (BN): used to represent the complex relationships between the various factors that contribute to coastal flow slides. Experimental study (ES): conducted laboratory and field experiments to investigate the physical processes involved in coastal flow slides. Site inspection (SI): visited coastal sites to collect data on the local conditions that may influence the risk of coastal flow slides. Sensitivity index development (SID): used to quantify the relative importance of different factors in contributing to coastal flow slides.

The hybrid model identified beach slope, sediment configuration and compaction, mass flow, and the existence of turbidity currents as the key variables that differentiate CRBF and LFS failures. To effectively handle the specific need of distinguishing between these two types of coastal failures, a tailored sensitivity index was developed in alignment with the hybrid model. This comprehensive metric incorporates various factors such as beach slope, sediment characteristics, and mass flow incidence, all crucial for assessing coastal vulnerability to failures like CRBF and LFS. The hybrid model not only identifies key variables like beach slope, sediment configuration, compaction, mass flow, and turbidity currents but also examines additional parameters. These parameters offer valuable insights into coastal management

strategies associated with these key variables. These additional parameters offer valuable insights into how the key variables are connected to strategies for coastal managment.

This study offers a novel approach by integrating the complementary strengths and functionalities of several models, (BN, ES, SI, SID), enabling researchers to make significant contributions to research in:

(a) expanding the scope of application by developing new methods for coastal flow slides; (b) considering a wider range of variables relevant to CFS; (c) analyzing variables that can have a significant impact on flow slides; (d) developing methodologies for coupling coastal flow slide projections with reliable outcomes.

YÖNETİM STRATEJİLERİ İLE BİRLİKTE KIYI HEYELANI İÇİN UYARLANMIŞ BİR HİBRİT RİSK DEĞERLENDİRME MODELİ

ÖZET

Kıyı heyelanı (KH), denize doğru ani bir çökme, kıyı bölgelerinde meydana gelen kum ve silt gibi kıyı malzemelerinin denize doğru kayması şeklinde ortaya çıkan bir olgudur.. İki farklı sınıfa ayrılabilirler: gedik açma ve sıvılaşma. Bunlardan ilki sıkıştırılmış kumda oluşur ve kum taneciklerinin boşluk basıncını düşürerek birbirinden ayrılmasıyla başlar. Bu, kum taneciklerinin kademeli bir süreçte tek tek aşağıya doğru akmasına neden olur. Sıvılaşma ise, kıyı malzemesinin aniden dayanıklılığını kaybetmesi ve sıvı gibi akması nedeniyle daha ani bir süreçtir.

Bu iki önemli konu, yani kıyı bölgelerindeki ani değişimler ve bunların yol açtığı çevresel ve insani etkiler, bilimsel literatürde oldukça nadir işlenen konulardır. Bu durum, bu alanlardaki araştırma eksikliklerinden kaynaklanmaktadır ve henüz yeterli sayıda çalışmaya ulaşılmamış olması, kıyı bölgelerindeki potansiyel tehlikelerin doğru şekilde anlaşılması ve yönetilmesinde büyük bir zorluk teşkil etmektedir. Su altı koşullarının karmaşıklığı, bu konuları derinlemesine ve kapsamlı bir şekilde analiz etmeyi daha da zorlaştırmakta, bu da risk analizi sürecini karmaşıklaştırır ve etkili bir şekilde yönetilmesini güçleştirir.

Bu iki olay, nadir görülen olaylar olsa da, olası büyük çevresel ve insani etkilere yol açabilir. Bu etkiler, kıyı ekosistemlerinin bozulmasından, insan yaşamı ve mülkiyetine doğrudan zarar verilmesine kadar değişebilir. Özellikle iklim değişikliği ve artan insan faaliyetleri göz önünde bulundurulduğunda, bu tehlikelerin boyutu daha da artmakta ve kıyı bölgeleri için ciddi riskler oluşturmaktadır. Bu nedenle, bu tür nadir ancak potansiyel olarak yıkıcı olayların doğru bir şekilde anlaşılması ve yönetilmesi, özellikle savunmasız kıyı bölgeleri için kritik bir öneme sahiptir.

Bu nedenle, daha fazla araştırma ve bilimsel çaba, bu tehlikelerin doğasını ve nedenlerini anlamak, gelecekteki riskleri azaltmak ve kıyı bölgelerini daha dayanıklı hale getirmek için hayati önem taşımaktadır. Bu araştırmalar, kıyı yönetimi politikalarının geliştirilmesi, kıyı altyapısının güçlendirilmesi ve yerel toplulukların bu tür olaylara karşı hazırlıklı olmalarını sağlamak için gereklidir.

Özellikle, iklim değişikliği ve deniz seviyelerinin yükselmesi, bu tür tehlikelerin artmasına katkı sağlamakta ve bu durum, Türkiye gibi gelgit farkının az olduğu ülkelerde bu tür olayların meydana gelmesi öngörülmektedir. Bu nedenle, bu konuda yapılacak bilimsel çalışmalar ve araştırmalar, bu tür tehlikelere karşı kıyı bölgelerini korumak ve bu alanlarda yaşayan toplulukların güvenliğini sağlamak için oldukça önemlidir. Bu çalışmalar, kıyı bölgelerinde yaşayan insanların yaşam kalitesini artıracak ve bu bölgelerdeki ekonomik ve çevresel sürdürülebilirliği sağlamak için gerekli olan bilgileri ve araçları sunacaktır.

Bu bağlamda, bu çalışma, KH riskinin değerlendirilmesi ve savunmasız kıyı bölgelerinin belirlenmesi için kullanılabilecek yeni bir duyarlılık indeksi ve bu konuya özel olarak bir hibrit model sunulmuştur. Hibrit model, geniş bir yelpazede dört farklı bileşeni içermektedir: Bayes ağı (BA), deneysel çalışma (DÇ), saha incelemesi (Sİ) ve duyarlılık indeksinin oluşturlması (DIO). Bu bileşenler, KH riskinin daha ayrıntılı bir şekilde analiz edilmesi ve kıyı bölgelerinin güvenliğini artırmak için kullanılabilir bir çerçevede oluşturulmuştur.

BA, olasılık temelli bir yaklaşım kullanarak veri analizini desteklemek amacıyla oluşturulmuştur. Deneysel çalışma (DÇ), laboratuvar deneyleri ve simülasyonlar yoluyla KH'nin etkilerini incelemek için kullanılır. Saha incelemesi (Sİ) ve saha ölçümleri (SÖ) yardımıyla gerçek verilerini toplanması ve modeli doğrulamak amacıyla yapılmıştır. Duyarlılık indeksi (DI), kıyı bölgelerinin risk seviyelerini belirlemek ve karar vericilere rehberlik etmek için oluşturulmuştur.

Hibrit model, beş farklı bileşenin yanısıra kıyıda gerisine doğru gedik açma (KGDGA) ve kıyının sıvılaşması (KS) gibi iki farklı olay örgüsünü birbirinden ayırt ederek, bu iki olay için önemli parametreleri barındırır. Bu iki farklı kıyı zararı türünü etkili bir şekilde birbirinden ayırmak ve anlamak amacıyla, hibrit modelle uyumlu bir duyarlılık indeksi özel olarak geliştirilmiştir. Bu indeks, kıyı bölgelerinin KGDGA ve KS'ye karşı savunmasızlığını değerlendirmek için kullanılan çeşitli faktörleri içermektedir.

Her sahil bölgesi benzersizdir ve farklı ihtiyaçlara sahiptir. Bu nedenle, hibrit model tarafından sunulan öneriler, her sahilin özgün koşullarını ve gereksinimlerini yansıtacak şekilde uyarlanabilir. Bu sayede, sahil bölgelerinin sürdürülebilir yönetimi için daha iyi bilgi temelinde daha etkili ve yerel ihtiyaçlara uygun politika ve planlar geliştirilebilir. Hibrit model, kıyı yöneticileri ve planlamacıları için güçlü bir araç olabilir ve sahil bölgelerinin gelecekteki sürdürülebilirliğini sağlamak için önemli bir katkı sunabilir.
Bu yaklaşım, gelecekteki riskleri daha iyi anlama ve minimize etme amacını taşırken, aynı zamanda savunmasız kıyı bölgelerinin güvenliğini artırmak ve çevresel sürdürülebilirliği sağlamak için önemli bir adım olarak değerlendirilebilir. Bu çalışma, KH riski ile ilgili yeni perspektifler sunarak, bilim insanlarına, kıyısal alanların yönetimini yapan kurum ve kuruluşlara ve kıyı bölgelerinde yaşayan topluluklara daha güçlü bir temel sağlamayı amaçlamaktadır. Bu sayede, gelecekteki tehlikelere karşı daha bilinçli ve hazırlıklı olmalarına yardımcı olurken, aynı zamanda kıyı bölgelerinde yaşayan insanların yaşamlarını ve mülkiyetlerini daha iyi koruma fırsatı sunmaktadır. Bu çalışmada, bu yeni perspektifleri desteklemek ve araştırmanın faydalarını daha da artırmak için, hybrid risk modelinin KH riskini değerlendirmedeki etkinliğini sunulmuştur. Çalışmanın ana amacı, hybrid risk modelin KH temel faktörlerin/parametrelerin bu olayı nasıl etkilediğine dair kapsamlı bir risk analizi sunmaktadır. Bütüncül bir yaklaşım açısı amacıyla bir çok parametre ele alınmıştır.
Bu çalışma, hibrit modelin güçlü özelliklerini kullanarak, aşağıdaki maddelerde belirtilen katkıları literatüre sunmayı amaçlamıştır:

a) Yeni yöntemler geliştirilerek uygulama kapsamının genişletilmesi; Bu çalışma, geleneksel kıyı yönetimi yaklaşımlarına yenilikçi bir bakış açısı getirerek, sahil bölgelerinin ani çöküş risklerini daha iyi anlamak ve daha etkili bir şekilde yönetmek için yeni yöntemler geliştirmiştir. Hibrit model, bu yöntemlerin kullanılmasını teşvik eder ve kıyı yöneticilerine daha fazla araç sunar.

b) Konuyla ilgili daha geniş bir değişken yelpazesini dikkate almak; Hibrit model, kıyı bölgelerinin yönetimini farklı değişkenleri de dikkate alarak ele alınmıştır. Bu, çevresel ve coğrafi faktörleri içeren geniş bir değişken yelpazesi ile zenginleştirilmesi hedeflenmiştir. Bu sayede, kıyı bölgelerinde meydana gelen bu tür kompleks olayların daha iyi anlaşılmasını sağlamak ve daha kapsamlı çözümler üretmek mümkün hale getirilmesi hedeflenmiştir.

c) Konu üzerinde önemli bir etkiye sahip olabilecek değişkenleri analiz etmek; Hibrit model, KH riskini etkileyen ve önemli bir etkiye sahip olabilecek değişkenleri analizleri yapılmıştır. Dolayısıyla, bu analizler yardımıyla sahil bölgelerinde meydana gelen bu tür risklerin belirlenmesi yapılarak ve bu risklerle karşı önlemler almak amacıyla geliştirilmiştir.

d) Konuyla ilgili tahminlerin ve sonuçların geçerliliğini ve güvenilirliğini güvence altına alacak metodolojiler oluşturmaktır: Bu metodolojiler yardımıyla beş farklı bileşen kullanılarak güvenilir ve geçerli sonuçlar üretmek üzere hedeflenmiştir . Bunun sonucunda ise, kıyı mühendisleri, kıyı yöneticileri ve politika yapıcıları için kritik öneme sahiptir, çünkü doğru ve güvenilir bilgilere dayalı kararlar alınmasını sağlar. Ayrıca, bu metodolojiler gelecekteki çalışmalara da rehberlik olacağı öngörülmektedir. KH konusu hakkında neredeyse hiç çalışma yapılmadığı söylenebilir, çünkü mevcut literatürde bu konuya dair çok sınırlı sayıda araştırma bulunmaktadır. Konuyla ilgili mevcut literatür göz önüne alındığında, bu çalışma yardımıyla yeni araştırmalar yapılarak bu konudaki bilgi birikimini artırmak ve bu alandaki temel sorunlara çözüm bulmak amacıyla katkı sağlanması gerektiği bakış açışıyla hazırlanmıştır.

1. INTRODUCTION

1.1 Background and Motivation

The study of coastal flow slides is very important in geology and coastal engineering. These events, characterised by the abrupt movement of soil or sediment down coastal slopes, may have far-reaching implications for both natural habitats and human infrastructure (Durap et al., 2023).

Understanding coastal flow slides is crucial for a variety of reasons. First and foremost, they provide a serious threat to coastal communities because they may hasten the erosion of shorelines, which might harm buildings and infrastructure and possibly put lives in danger. By conducting a complete analysis of these occurrences, we can enhance our ability to evaluate and effectively address the risks that are linked to them (Mastbergen et al., 2019).

In addition, it is important to note that coastal flow slides may have significant environmental consequences. The possible consequences of their presence include the disruption of fragile ecosystems, modification of sediment transport patterns, and potential damage to marine organisms. Through a comprehensive comprehension of the processes and triggers associated with coastal flow slides, it becomes possible to formulate and implement solutions aimed at the preservation and safeguarding of coastal habitats (You et al., 2012).

Furthermore, the investigation of coastal flow slides has significant importance in the context of promoting sustainable coastal management and engineering practises. The use of suitable technical solutions, such as stabilisation measures or early warning systems, enables the design and implementation of strategies to minimise the dangers associated with flow slides (Brothers et al., 2019).

When taken as a whole, the study of coastal flow slides is not just about gaining a knowledge of a geological occurrence; rather, it is also about protecting coastal populations, maintaining natural habitats, and making certain that sustainable development may take place along the shore (Richard et al., 2020).

A significant incident took place in the year 1969 within the city of Nelson, located in New Zealand. The incident of a CFS resulted in the unfortunate demise of 17 individuals, therefore emphasising the profound and detrimental consequences that such incidents may impose upon people living in close proximity to coastal regions. This occurrence underscored the need of timely alert systems and thorough risk evaluations in order to avert such calamities in other instances.

In 1998, an additional noteworthy incidence occurred within the context of Papua New Guinea. A significant geological event occurred in the Boluminski Gulf, resulting in a substantial landslip and subsequent tsunami that had an impact on many coastal settlements. The catastrophic event resulted in the loss of around 2,200 people, making it one of the most lethal tsunamis caused by landslides in documented history. The occurrence of this disaster has emphasised the pressing need for precise risk assessment models capable of forecasting the probable consequences of coastal flow slides and providing guidance for mitigating actions.

In recent years, the increasing occurrence of severe weather events and phenomena associated with climate change has amplified the vulnerability to coastal flow slides. Various flow slide episodes throughout the globe have been associated with phenomena such as intense precipitation, storm surges, and quick snowmelt. Prominent occurrences include the 27/01/2019 Ameland coastal flow slides in Netherlands, as well as the 15/7/2016 Seabrook Island slides in USA. The events mentioned above highlight the need of accurate risk assessment models that can include dynamic climatic factors and their influence on the stability of coastal regions.

The tabulated events in Table 1.1 offers a structured examination of coastal flow slide occurrences, including volumetric assessments and spatial coordinates.

Table 1.1 : Coastal flow slide events: notable incidents sorted by date (Durap et al., 2023; Mastbergen et al., 2019).

Location	Year/Date	Volume (1000 m3)	Channel Depth (m)	Retrogression Length (m)	Latitude (N)	Longitude (E)
Plaat van Ossenisse, Netherlands	2018	1100	37	555	51°25′34.42″N	4°0′12.74″E
Plaat van Walsoorden, Netherlands	1.10.2014	60	6	90	51°22′38.02″N	4°4′5.45″E
Plaat van Walsoorden, Netherlands	22.7.2014	850	25	375	51°22′42.10″N	4°4′1.70″E
Cap Ferret, Bassin d'Arcachon, France	8.2.2018	-	22	330	44°37′17.32″N	1°14′44.49″W
Hoofdplaatpolder, Netherlands	10.6.1964	-	30	208	51°22′51.39″N	3°37′3.32″E
Oost-Vlieland, Netherlands	1.2.2006	18	20	300	53°17′43.05″N	5°5′34.83″E
Eastern Scheldt Barrier, Netherlands	2007	850	30	450	51°36′59.26″N	3°40′31.26″E
Jumpinpin, NSW, Australia	24.11.2016	-	20	300	27°43′43.50″S	153°26′57.52″E
Inskip Point, QL, Australia	2.4.2016	-	-	300	25°48′31″S	153°03′38″E
Inskip Point, QL, Australia	26.9.2015	-	22	330	25°48′32.96″S	153°3′39.93″E
Vlietepolder, Netherlands	28.10.1886	540	40	380	51°35′55.53″N	3°44′57.32″E
Vlietepolder, Netherlands	10.3.1864	195	24	320	51°36′2.03″N	3°45′27.86″E
Oud Noord-Bevelandse Polder, Neth.	11.8.1881	-	34	185	51°36′18.30″N	3°47′53.01″E
Amity Point, QL, Australia	17.8.2014	-	14	210	27°23′35″S	153°26′23″E

The motivation of the present study is that conducting a tailored risk assessment for coastal flow slides arises from the necessity to gain a deeper comprehension and alleviate the linked hazards. Coastal management and disaster preparation relies heavily on these kinds of evaluations, and this is especially the case in locations where coastal populations and ecosystems are particularly at risk. By conducting a methodical assessment of the relevant parameters that influence the frequency and impact of coastal flow slide incidents, it is possible to develop well-informed plans aimed at mitigating risks and effectively responding to such events.

Key motivations for this tailored risk assessment include:

Vulnerability of Coastal Regions: Coastal areas, with their high population densities and economic significance, are prime targets for the adverse impacts of flow slides, presenting a formidable threat to both the communities inhabiting coastal regions and the economic assets concentrated there. Given their vulnerability to such events, it is imperative for coastal communities to implement proactive measures to mitigate the risks posed by flow slides, as failure to do so could result in devastating consequences for both lives and livelihoods in these vital coastal zones. To protect people and property, it is necessary to understand the unique risks posed by these areas.

Changing Climate Patterns and Hydraulic Gradient Level: Due to shifting climate patterns, coastal regions are currently witnessing a rise in the occurrence and severity of rainfall events, leading to an increased likelihood of flow slides by increasing the level of hydraulic gradient, which refers to the slope or rate of change of hydraulic head (water pressure) along a flow path. Moreover, when high tide comes in, the groundwater level tends to rise as well. Once the tide level drops, the groundwater level might not immediately stabilize itself depending on the types of soil characteristics. This lack of immediate stabilization can lead to the landward groundwater level remaining high, creating a hydraulic gradient level difference between landward and seaward areas.

A risk assessment can facilitate the process of adapting to the evolving conditions, forecasting potential future risks, and considering the heightened probability of intense rainfall. Furthermore, fluctuations in hydraulic gradient levels during periods of low tide and high tide are of utmost importance in the dynamics of groundwater, as they have a significant impact on slope stability.

Groundwater Level and Sea-Level Rise: The increasing groundwater level and sea-level rise are exacerbating issues in coastal regions. The presence of elevated groundwater levels has the potential to heighten the instability of coastal slope, whilst the phenomenon of increasing sea levels may further intensify the dangers associated with erosion, flooding, and coastal flow slides. Both characteristics are essential considerations when evaluating the danger of coastal flow slides.

Environmental Conservation: Coastal ecosystems hold great ecological significance and are characterised by their delicate nature. The presence of flow slides can have negative consequences on ecosystems, underscoring the importance of evaluating and addressing potential risks to biodiversity and natural habitats.

Infrastructure Resilience: Coastal regions often accommodate critical infrastructure, such as ports, roads, and residential areas. Evaluating the risk of flow slides is essential for ensuring the resilience of infrastructure systems, particularly in light of groundwater conditions.

Regulatory Compliance: Different geographical regions have specific legal obligations when it comes to the assessment and monitoring of geohazards. A specialised risk assessment enables organisations and agencies to effectively fulfil these duties.

1.2 Research Questions

In the pursuit of a comprehensive understanding of coastal flow slide risk, this study addresses the following research questions:

What are the key factors contributing to the occurrence of coastal flow slides, and how can they be systematically studied and understood?

Hydraulic conductivity, which denotes a material's capacity to transmit fluids through its pores or interstitial spaces, is a fundamental concept in hydrogeology and soil mechanics. This property holds significant importance in understanding various natural processes, including groundwater flow, soil erosion, and contaminant transport.

Given this understanding of hydraulic conductivity, how does the variability in conductivity among different types of sand influence the risk of coastal flow slides? Moreover, what reliable methods exist for precisely measuring this property?

How do changing climate patterns, including increased rainfall intensity, influence the occurrence and frequency of coastal flow slides?

What is the relationship between grain size distribution in coastal sands and their susceptibility to flow slides, and how can this relationship be quantified?

How do variations in volume fraction, using water and oil silicone, impact the porosity and stability of coastal sands, and what insights can be gained for risk assessment?

What are the breach characteristics, including height and velocity, during coastal flow slide events, and how do they correlate with the potential for catastrophic failures?

How does tapping and compaction influence the solid fraction of coastal sands, and how can this knowledge be applied to assess the risk of flow slides under different conditions?

How do field measurements, such as current measurements, tide levels, and groundwater levels, contribute to understanding the dynamics and risk of coastal flow slides in specific locations, like Amity Point?

What is the relationship between variations in hydraulic gradient levels, particularly during low tide and high tide, and the susceptibility of coastal sediments to flow slides?

How do rising groundwater levels and sea-level rise contribute to the destabilization of coastal sediments and their potential for flow slides?

What are the environmental implications of coastal flow slides on fragile coastal ecosystems, and how can these risks be mitigated?

What are the key findings from various experiments and field measurements, and how can they be synthesized to provide a comprehensive assessment of coastal flow slide risk?

In light of these research questions, the objective of this study is to conduct a thorough analysis of the risk of coastal flow slides. This was achieved through a series of experiments and field measurements. We aim to enhance the knowledge base for making informed decisions and implementing risk reduction strategies in coastal regions susceptible to flow slides. This was achieved by analysing factors such as hydraulic conductivity, sediment characteristics, breach dynamics, groundwater level, sea-level rise, and field data. The purpose of this research is to improve our understanding of the processes involved in coastal flow slides and to develop practical recommendations for reducing the risk associated with them. Ultimately, the goal of this study is to enhance the safety and sustainability of coastal communities and environments.

1.3 Research Objectives

The study outlined in this thesis aims to achieve several and essential goals in order to further our understanding of coastal flow slides. These objectives function as a strategic plan towards a complete approach that incorporates several crucial aspects:

- The primary objective of this study is to develop a rigorous approach for effectively combining forecasts of coastal flow slides with reliable and consistent results. This entails the creation of models and technologies that have the capability to provide precise predictions, enabling prompt and efficient implementation of reaction strategies.
- Subsequently, the secondary aim is to assess the efficacy of the developed approach through rigorous testing and validation protocols. This encompasses a thorough examination of model predictions in relation to observed data, ensuring the accuracy and dependability of the results.
- Furthermore, this study pursues a dual objective approach. Firstly, it endeavors to broaden the application scope by devising a comprehensive technique that encompasses various pertinent components essential for understanding coastal flow slides. Secondly, it aims to employ this approach to provide a comprehensive perspective on these phenomena, ensuring that no critical aspect is overlooked during the examination.
- Recognizing the paramount importance of particle size in relation to critical slope failure angles, particularly concerning the incorporation of particle diameter variability, this study component seeks to elucidate the diverse spectrum of particle sizes that may influence the occurrence and dynamics of

flow slides in coastal regions. By engaging in this practice, it facilitates a more intricate and precise evaluation of potential hazards involved.

- Lastly, the present research undertakes a thorough investigation of key factors with significant potential to influence the occurrence of flow slides. This entails a comprehensive analysis of geological, environmental, topographical variables, among others, which collectively contribute to the probability and magnitude of coastal flow slide events.

In conclusion, these objectives together contribute to a holistic endeavour aiming at enhancing our comprehension of geological phenomena, including those related to breach and liquefaction flow slides. Furthermore, these entities play a crucial role in the development of highly efficient approaches for evaluating and managing the hazards linked to coastal flow slide occurrences. This study aims to not only expand our understanding but also develop pragmatic strategies to protect coastal populations from the potentially catastrophic consequences of these occurrences.

1.4 Problem Definition And What Requires To Trigger Coastal Flow Slides:

Coastal flow slides (CFS) is a geomorphological phenomenon that occurs on underwater slopes near coastlines. They involve the rapid downslope movement and redeposition of large volumes of sediment. CFS stands out from other coastal morphological changes, such as sediment transport and erosion, by its dramatic nature.

Difference between coastal flow slides vs coastal sediment transport and landslides can be given with the following statements:

Coastal flow slides: These are rapid downslope movements of sediment in a fluid-like manner that occur underwater near coastlines. They are primarily triggered by tidal fluctuations and hydraulic gradient differences between shoreward to seaward.

Coastal sediment transport: This refers to the natural movement of sediment along coastlines due to wave action, currents, and tides. It does not involve the rapid downslope movement seen in coastal flow slides.

Landslides: Landslides typically occur on land, not underwater. They are triggered by various factors like rainfall, seismic activity, or human activities. Landslides involve the sudden movement of soil, rock, or debris down a slope.

Since, CFS exhibits distinct characteristics necessitating a tailored analytical and management framework. CFS can be likened to observing a segment of the coastal beachfront undergoing a sudden disintegration and subsequent displacement into ocean. CFS transformations require specific conditions to be triggered. The following is an exploration of the key factors involved in the onset of CFS. In order for CFS to take place, certain conditions or key factors must be present or satisfied:

Coastal flow slides (CFS) stand out from other coastal morphological changes, like sediment transport and erosion, due to their dramatic nature. Unlike the gradual shifts seen in those processes, CFS involve sudden, rapid downslope movement of massive sediment volumes, causing a significant and instantaneous reshaping of the underwater landscape. Imagine a large chunk of the beach breaking away and flowing downhill instead of slowly eroding bit by bit - that's the power of a coastal flow slide.

High tidal range: Coastal flow slides are more likely to occur in areas with a high tidal range, where there is a significant difference between high and low tides.

Groundwater level fluctuations: The movement of high tides can increase groundwater levels, and when tides recede, the groundwater levels may remain elevated. This fluctuation creates hydraulic gradient differences.

Hydraulic gradient differences: The interaction between tidal changes and hydraulic gradient differences plays a critical role in the dynamics of coastal regions. When the tide is high, it exerts its influence not only on the shoreline but also on the underlying groundwater system. As the high tide inundates the coastal area, it increases the groundwater level in the vicinity of the shore. This rise in the groundwater level is a direct result of the seawater infiltrating into the land, creating a hydraulic connection between the sea and the groundwater aquifer.

However, when the tide eventually recedes, a complex interplay of forces and gradients comes into play. At this point, the groundwater level cannot simply remain static due to the hydraulic gradient differences between the landward and seaward directions.

What these hydraulic gradient differences effectively do is to seek equilibrium, a balance between the high-energy conditions landward and the lower-energy conditions seaward. In the landward direction, where the energy is higher, the groundwater is subjected to greater pressure force from the hydraulic gradient. To reach equilibrium and stabilize itself, the groundwater begins to flow from this high-energy landward area towards the low-energy seaward region.

When there is a significant hydraulic gradient difference, it can lead to high pressure force to beach, causing it to disintegrate into fragmented pieces that cascade down towards the offshore direction.

Sediment accumulation: As the tide shifts from high to low levels, sediment accumulates along the shoreline, leading to the compaction of soil.

Slope: As the process of sediment accumulation continues to take place along a specific shoreline, this gradual buildup of sediment materials intensifies over time. Consequently, this continuous accumulation of sediment contributes to the formation of a steeper coastal slope or incline, thereby altering the overall topography and morphology of the shoreline.

Coastal flow slides are significantly influenced by the interplay between beach slope and tidal dynamics. The difference between steeper and flatter beaches plays a pivotal role, primarily driven by hydraulic gradient and force pressure:

Hydraulic Gradient:

- Steeper Beaches: These exhibit a higher hydraulic gradient, causing rapid tide changes over shorter horizontal distances. However, the total vertical tidal range may be limited due to less surface area submerged.

- Flatter Beaches: Conversely, flatter beaches feature a lower hydraulic gradient, leading to slower tide transitions that can cover more extensive areas, potentially resulting in a greater vertical tidal range.

Force Pressure:

- Steeper Beaches: Water on steep slopes experiences a more substantial gravitational pull, generating higher force pressure during high tide. This heightened pressure can intensify beach erosion and scouring.

- Flatter Beaches: On flatter slopes, the gravitational pull is weaker, resulting in reduced force pressure on the beach, causing less erosion and a gentler tidal effect.

In combination, these factors affect tidal range and beach impact. Steeper beaches may have quicker tides but smaller vertical ranges, and they face concentrated force pressure, potentially leading to erosion. Flatter beaches experience gentler tides, larger vertical ranges, and less force pressure, potentially resulting in reduced erosion. The overall impact depends on seabed topography and local tidal patterns.

Soil compaction: When the sediment accumulates and compacts, it can restrict the flow of water through the porous media of the soil.

Certain soil characteristics: The evaluation of certain soil characteristics is of paramount importance due to their direct impact on coastal morphology and stability. These characteristics encompass a range of factors including the diversity of soil shapes, variations in hydraulic conductivity, and notably, the angle of internal friction in both dry and wet conditions.

A key aspect to consider is the angle of internal friction. A high angle of internal friction, particularly when exhibiting minimal variance between dry and wet states, indicates a soil's enhanced stability and increased resistance to shear stress. This property is crucial in maintaining the structural integrity of coastal regions, as it determines the soil's ability to withstand various environmental stresses.

However, this scenario becomes more complex when considering the effects of tidal influences. In instances of a high tidal range, the groundwater level is subject to significant fluctuations, leading to an increase in the hydraulic gradient between the landward and seaward sides. This rise in the hydraulic gradient is pivotal as it intensifies the pressure differential across the soil mass.

Given the high angle of internal friction, which naturally restricts water flow through the soil's pore spaces, the hydraulic gradient attempts to seek equilibrium but is impeded. This blockage creates a scenario where the water cannot percolate efficiently through the soil matrix. As a result, when the hydraulic pressure exceeds the soil's capacity to resist, coastal flow slides may occur. These slides represent a significant geomorphological process, where large sections of the coastline are displaced due to the inability of the soil structure to balance the hydraulic forces.

Therefore, the interaction between the angle of internal friction and the hydraulic gradient under varying tidal conditions is a critical factor in coastal stability. Understanding this dynamic is essential for predicting potential coastal flow slides and implementing effective coastal management strategies to mitigate the risks associated with these geomorphological changes.

1.5 Overview of the Methodology: Elucidating Triggers of Coastal Flow Slides Through A Combined Field and Laboratory Investigation

In this research, we adopted the following approach based on the given problem definition and the prerequisites for the occurrence of Coastal Flow Slides (CFS):

For the high tide fluctuations: Australia is renowned for its substantial high tide fluctuations. As previously discussed in the problem definition section, CFS is more likely to occur in areas with a high tidal range, where there is a significant difference between high and low tides. However, recognizing the potential for CFS solely based on tidal range is insufficient for a thorough investigation. It is imperative to observe actual CFS events to conduct a comprehensive analysis.

For this reason, we selected Amity Point, situated on North Stradbroke Island (Minjerribah), which is known for its high tidal fluctuations. With coordinates at 27.3952°S latitude and 153.4411°E longitude, North Stradbroke Island is the second-largest sand island in the world, located within Australia. This location was chosen specifically because it has a history of CFS occurrences, making it an ideal site for this investigation.

To assess the tidal range, we conducted measurements on-site at Amity Point. Additionally, we obtained tidal range data from the meteorological station of Queensland, Australia, to ensure comprehensive and accurate information for this particular analysis. This dual approach allowed us to gather both real-time and historical data on tide range fluctuations in the Amity Point area, contributing to a comprehensive understanding of the coastal dynamics in this region.

Groundwater level fluctuations: We measured groundwater level fluctuations using groundwater wells strategically placed in the study area. The movement of high tides can significantly impact groundwater levels, with the potential for elevated levels persisting even as tides recede. This fluctuation in groundwater levels creates hydraulic gradient differences, which can play a crucial role in understanding the conditions leading to CFS events. By monitoring these groundwater level fluctuations, we aimed to gain insights into the complex interplay between tides, groundwater, and coastal stability.

Hydraulic gradient differences: To understand the impact of hydraulic gradient differences on coastal flow slides (CFS), we conducted a comprehensive investigation using two main approaches:

Site inspection: We conducted on-site inspections to observe how hydraulic gradients are affected by tidal range, leading to fluctuations in groundwater levels and the subsequent creation of hydraulic differences between the landward and seaward sides of the study area. During these inspections, we carefully monitored the changes in groundwater levels and hydraulic gradients in response to tidal fluctuations. This direct observation allowed us to gather real-time data on the complex interactions between tidal forces and groundwater flow.

Tilting box experimental study: In addition to the site inspections, we conducted tilting box experiments to further explore hydraulic gradient differences. In these experiments, we utilized body force to tilt the box. As the box tilted, the water surface within it remained almost horizontal due to its free movement. However, the submerged soil within the box experienced a gravitational force, pulling it downward. This gravitational force created a pressure difference between the water at the higher end and the lower end of the box, resulting in the development of a hydraulic gradient within the saturated soil layer.

Sediment Accumulation: To comprehensively investigate the role of sediment accumulation in the initiation and development of coastal flow slides (CFS), we employed a dual-pronged approach, utilizing both site inspections and tilting box experimental studies:

Site inspection: Through on-site inspections, we aimed to gain insights into how sediment accumulation contributes to the creation of steep slopes, which, in turn, can lead to CFS events. During these inspections, we closely observed and documented the sediment deposition patterns along the coastline. By studying the real-world effects of sediment accumulation on coastal topography, we were able to identify areas prone to CFS due to steep slope formations resulting from sediment buildup.

Tilting box experimental study: In the tilting box experiments, we explored the relationship between sediment accumulation and CFS in a controlled laboratory setting. To address various scenarios related to CFS, we established different angles within the tilting box, simulating coastal slope angles. It is well-established that CFS is highly influenced by the underwater sediment's slope angle. By tilting the box to different angles, we replicated various real-world slope scenarios and observed how these angles affected the initiation, development, and runout of CFS.

These tilting box experiments allowed us to systematically study the impact of sediment accumulation on coastal slope stability and its direct connection to CFS occurrences. By combining on-site inspections with controlled laboratory experiments, we gained a comprehensive understanding of the critical role played by sediment accumulation in the dynamics of CFS events, from coastal topography to the underlying mechanisms of failure.

Slope: The role of coastal slope in the occurrence of coastal flow slides (CFS) was investigated through a two-fold approach encompassing both site inspections and tilting box experimental studies:

Site inspection: Site inspections were conducted to examine how coastal slope is affected by sediment accumulation, ultimately leading to the creation of steep slopes. During these inspections, we carefully assessed the coastal topography and documented any changes in slope due to sediment buildup. The aim was to understand how sediment accumulation contributes to the formation of steep coastal slopes, a critical factor in the potential initiation of CFS events.

Tilting box experimental study: In the laboratory experiments using a tilting box, we explored the impact of slope on CFS under controlled conditions. The tilting box allowed us to establish different angles of slope inside the box, simulating various coastal slope scenarios. To create slope within the box, we used body force for tilting. This approach enabled us to systematically examine how varying slope angles affect the likelihood and dynamics of CFS.

These investigations provided valuable insights into the complex relationship between coastal slope, sediment accumulation, and CFS events, shedding light on the mechanisms and contributing factors associated with CFS occurrences.

Compaction: The impact of soil compaction on the occurrence of coastal flow slides (CFS) was comprehensively studied through a dual approach involving site inspections and controlled laboratory experiments:

Site inspection: Through site inspections were conducted to assess how sediment accumulation can lead to the compaction of a certain part of Amity Point beach. As sediment accumulates, it can compact over time, restricting water percolation into the sea. This compaction is driven by the hydraulic gradient seeking equilibrium, which, in turn, contributes to the fragmentation of the beach and the flow of materials into the ocean.

Tilting box and hydraulic conductivity experimental studies: In laboratory experiments, we explored the relationship between compaction and CFS using a tilting box and hydraulic conductivity studies. To simulate compaction, we employed a tapping method, varying the number of taps (0 taps, 3 taps, 5 taps, 10 taps, 20 taps, 40 taps, 50 taps, 80 taps, and 200 taps) as a compaction test. The tapping was applied to the soil within the box. The goal was to understand how compaction, represented by the number of taps, influences the likelihood of CFS.

Additionally, we conducted experiments using different fluids to assess how they interact with the materials and create a range of porosity. This involved varying fluid properties such as viscosity, retreating velocity, and grain density, along with factors such as d50 and d90/d10 ratios. These comprehensive tests provided insights into the complex relationship between material properties, fluid behavior, and the porosity of the soil, contributing to our understanding of the mechanisms that lead to CFS events in coastal environments.

Certain soil characteristics: The assessment of specific soil characteristics is of great importance because of their direct influence on coastal morphology and stability. These characteristics include various factors such as the diversity of soil shapes, variations in hydraulic conductivity and, in particular, the angle of internal friction in both dry and wet conditions.

This dynamic knowledge is essential for predicting potential coastal flow slides and implementing effective coastal management strategies to mitigate the risks associated with these geomorphological changes.

Laboratory investigations were undertaken with the primary objective of determining critical diameter ranges, compaction levels, porosity, dilation potential, and the mechanism responsible for delivering the necessary compaction through water waves. In this research, we investigated these critical soil characteristics using a combination of methods:

• Tilting box and hydraulic conductivity tests: We conducted a series of experiments using a tilting box to measure the angle of sliding failure of different sandy materials, including Amity Point sand, d50 = 0.15 mm, 0.54 mm, and 1.7 mm. These tests considered variations in sand compaction and saturation, aiming to understand the influence of geo-mechanical and fluid properties on the friction angle and the rate of retreat. The results of these experiments provided valuable insights into the relationship between soil characteristics and coastal stability.

• Compaction tests: To determine the dry and wet solids fraction of each sandy material, we conducted compaction tests. These tests involved filling a measuring cylinder with sand, tapping it to reach appropriate compaction, and measuring the dry volume of sand at various increments. The results allowed us to calculate the solids fraction, providing an indication of pore space and porosity within the material.

• Experiments with glass beads: We also conducted experiments using glass beads to validate the effects of different material morphological characteristics on the friction angle. The non-angular, smooth surface and spherical shape of glass beads were expected to result in a relatively low friction angle compared to angular coarse-grained sandy materials.

Through these comprehensive tests, we gained valuable insights into how specific soil characteristics, such as the angle of internal friction, influence coastal flow slides under varying conditions. This research contributes to a deeper understanding of coastal stability dynamics and the factors contributing to geomorphological changes in coastal environments.

Angle of internal friction: The angle of internal friction is an important aspect to have regard to. A high angle of friction, especially with minimal dry/wet variation, indicates a soil's increased stability and resistance to shear stress. These characteristics are essential for maintaining the structural integrity of coastal areas, since they determine the resilience of soils to a variety of environmental stresses.

In this research, it was conducted a comprehensive evaluation of the angle of internal friction through a series of "tilting box" experiments. These experiments aimed to measure the angle of sliding failure of different sandy materials under varying geo-mechanical and hydrological conditions. By altering multiple parameters, including sand compaction and sand saturation, the objective of this study was to distinguish the influence of these geo-mechanical and fluid properties on the friction angle, which, in turn, impacts the rate of retreat in coastal settings.

The experimental setup involved a rectangular-shaped glass box with dimensions of 49.5 x 39.5 x 10 cm. To initiate the experiments, we recorded both the volume and weight of the sand used before placing it into the tilting box. Subsequently, the sand was carefully poured into the box, and efforts were made to ensure that the sand surface was smoothed until it became horizontal. The initial height of the sand without compaction was also recorded.

The core of these experiments lay in gradually tilting the box until the sliding failure of the sand was observed. The angle at which this sliding failure occurred was meticulously measured and recorded. To ensure the reliability of the findings of this study, the entire process was repeated two additional times.

Following the completion of tests for uncompacted sand, we proceeded to examine the effects of compaction. Two different sand compaction heights were tested using the same method, providing valuable insights into how compaction influences the friction angle.

Additionally, we extended these experiments to investigate the wet friction angle. This involved filling the box with water and saturating the sand within it to replicate conditions closer to those found in coastal environments.

The outcomes of these tilting box experiments allowed us to gain a comprehensive understanding of the angle of internal friction under varying conditions, shedding light on its role in coastal stability dynamics and its influence on the potential for coastal flow slides. This research contributes significantly to the broader understanding of coastal geomorphology and the factors governing coastal region integrity.

1.6 Scope and Limitations

The primary objective of this research is to investigate the occurrence and characteristics of coastal flow slides, with a special emphasis on breach and liquefaction flow slides. This study involves a thorough analysis of several crucial aspects that impact the occurrence, behaviour, and possible hazards connected with these geological events. However, it is important to acknowledge certain limitations that may impact the research outcomes:

Geographical Scope: The focus of this study largely revolves on coastal regions, with a special emphasis on the analysis of flow slides that occur within these particular ecosystems. Nevertheless, it is crucial to recognize that this limited scope may not comprehensively capture or consider instances of flow slides in inland areas, namely those linked to riverbanks, which could display comparable features and causes.

There is considerable variation in the geological composition of riverbanks and coastal regions. Inland locations exhibit variations in soil composition, rock formations, and sedimentary layers, which all influence their vulnerability to river slides.

The major focus of the research on coastal locations may limit its ability to provide a thorough knowledge of flow slides occurring in inland regions, particularly those associated with river systems. Inland locations may exhibit unique geological, hydrological, and environmental characteristics that might impact the occurrence and dynamics of flow slides, perhaps differing from those seen in coastal areas.

Seismic Activity**:** Seismic activity has the potential to cause or worsen coastal flow slides, which are characterised by the occurrence of earthquakes or other seismic events. It may be necessary for the research to consider the seismic activity of the area.

Land Use: Land use changes, such as the process of urbanisation or modifications in agricultural practises, have the potential to modify surface features and alter drainage patterns. These alterations may subsequently influence the vulnerability of an area to flow slides.

2. LITERATURE REVIEW

2.1 Overview of Coastal Flow Slides

This section aims to provide a thorough comprehension of coastal flow slides, with a particular emphasis on differentiating between two basic groups based on the underlying geomechanical failure processes (Durap et al., 2023). Understanding these processes is crucial within the framework of coastal engineering and the reduction of hazards.

When the soil in coastal areas becomes unstable and loses its strength owing to the presence of water, liquefaction flow slides may occur. Because of this, coastal towns and infrastructure are at risk of massive landslides and flow flows.

When soil is saturated with water and then shaken or exposed to additional forces, such as wave action or storm surge, liquefaction may occur. This may lead to a decrease in the soil's bearing capacity, as the soil particles lose contact with one another and become more fluid-like.

Liquefaction may be caused by earthquakes, storm surges, and intense rainfall in coastal locations. Liquefaction may cause a mass of saturated silt to flow downslope, often with additional debris. This poses a serious threat to human life and may have devastating effects on coastal infrastructure including buildings, roads, and bridges. The occurrence of coastal liquefaction flow slides is difficult to predict because of the complexity of the event. Nevertheless, a variety of variables, such as the soil's type and composition, the availability of water in the soil, and the severity and length of the triggering event, might enhance the probability of such occurrences. The same applies to coastal breaching failure, which is also influenced by various factors that need to be carefully analyzed and accounted for in risk management strategies. Coastal engineers and Marine Spatial Planners may take many steps to reduce the likelihood of liquefaction flow slides occurring along the coast. Some of these measures include the use of deep foundations or reinforced concrete in the building of coastal structures to resist the effects of liquefaction. Coastal areas may also lessen the likelihood of soil liquefaction by taking measures such as enhancing drainage and decreasing soil moisture. Overall, coastal liquefaction flow slides pose a serious threat to coastal populations and infrastructure, necessitating cautious preparation and mitigating measures to lessen the likelihood of destruction and casualties.

Liquefaction flow slides basically develop in granular soils that exhibit little compaction, leading to a significant rise in pore water pressure compared to the surrounding ambient pressure levels. The increase in pressure may be ascribed to the compaction of the sand matrix inside the soil. Once liquefaction occurs, the bulk of sand undergoes a rapid and sudden downslope displacement. Generally, these motions have a rather little duration, sometimes spanning just a few minutes. The rapid movement seen during the process of liquefaction might provide noteworthy ramifications in coastal regions, hence demanding meticulous surveillance and implementation of techniques for mitigation (Alhaddad et al., 2023).

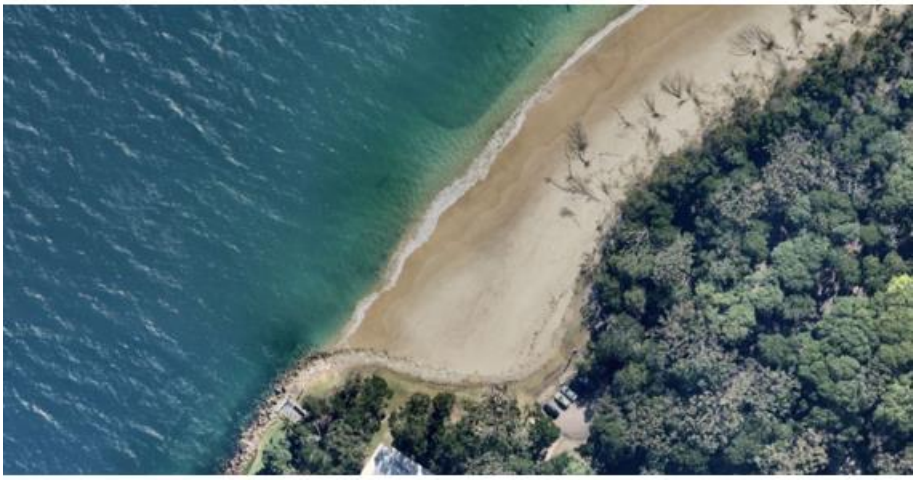
On the other hand, breach flow slides are distinctive events that occur inside strongly consolidated sand strata. In this observation, a reduction in pore water pressure is seen in relation to the surrounding ambient levels. The observed decrease in pressure may be elucidated by the expansion of the sand framework, resulting in phenomena such as suction or strain hardening. These processes works together in order to achieve stabilisation of the sand mass, leading to the formation and continuous existence of progressively retreating vertical sand barriers below the water's surface, usually known as "breaches." In contrast to liquefaction flow slides, breach flow slides have the ability to endure for prolonged durations due to the gradual downward movement of individual sand grains along the breach face. The previously mentioned phenomenon induces turbulent density currents which facilitate the downslope transportation of sand particles until they ultimately reach a condition of equilibrium (Durap et al., 2023).

Coastal breach failure can occur in the nearshore zone when slope stability is locally broken (e.g., due to dredging or incision by currents). It is essential to note when evaluating safety that breaching may cause a “destabilizing” effect if the height of the breach face increases, leading to an uncontrolled retrogressive failure of the slope (Alhaddad et al., 2023).

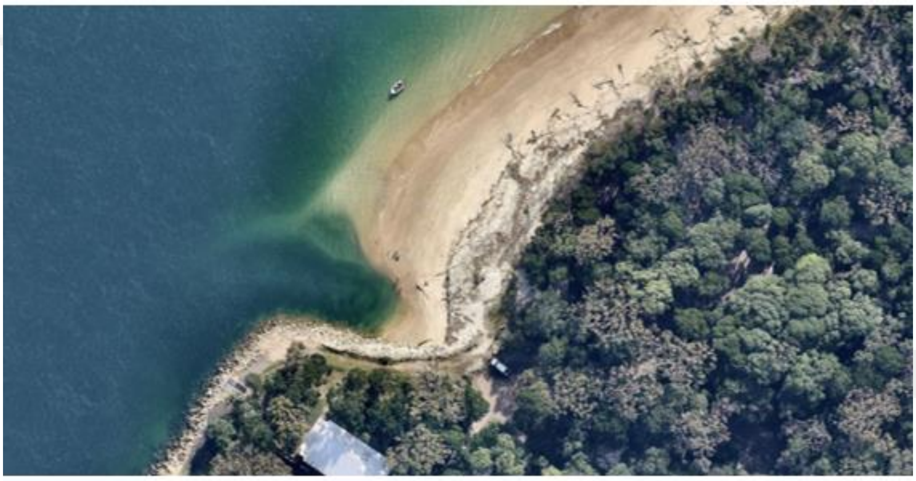
The occurrence of flow slides on Amity Point beach, a minuscule seaside settlement situated on North Stradbroke Island in the state of Queensland, Australia, is influenced by a combination of factors, including the geological composition of the coastline, wave action, tidal forces, and even human activities in the area (van Dijk et al., 2018). Amity Point is known for its an instance of Coastal Retrogressive Breaching Failure (CRBF), also known as dilative slope failure. Understanding the underlying causes and patterns of these flow slides is crucial for coastal resilience and hazard mitigation.

Figure 2.1 shows the occurrence of a coastal flow slide on the Amity Point beach. Photo (a) displays the beach before the flow slide event, while photo (b) shows the beach during the flow slide event. In this figure, as can seen the failure of the coastal slope, which results in the movement of sand toward the sea. Photo (c) displays the aftermath of the flow slide event, where the beach has undergone significant changes due to the movement of sand and debris. The occurrence of coastal flow slides, as demonstrated in this figure, can have severe impacts on the coastal environment and can result in the loss of important habitats for marine life. Understanding the mechanisms and potential triggers of flow slides is crucial to effectively manage and mitigate their impacts, as discussed in the preceding sections.

Figure 2.1: Flow slide occurrence on the Amity Point beach.



a) Satellite view of Amity point before coastal flow slide



b) Satellite view of coastal flow slides

Figure 2.2: Aerial images of Amity Point: pre and post flow**.**

To enhance our understanding of these processes, this research introduces a hybrid probabilistic model that can simulate the processes of coastal flow slides, including liquefaction flow slides. The model combines probabilistic approaches with numerical models to provide a more accurate representation of the underlying processes.

2.2 Coastal Flow Slides and Risk Assessment

Coastal flow slides, also referred to as retrogressive breaching failure or coastal slope failures, are geological phenomena characterized by the downward displacement of soil, rock, or debris down inclined surfaces within coastal regions (Durap et al., 2023). These incidents may have possible implications of coastal flow slides. Presented below is an overview of some significant discoveries:

Factors contributing to coastal flow slides occurrences:

• The occurrence of heavy rainfall may lead to the saturation of soil, resulting in a decrease in its stability and the subsequent initiation of landslides (Mastbergen et al., 2019).

• Wave activity may result in the erosion and undercutting of coastal slopes, which can ultimately lead to their collapse (Alhaddad et al., 2020).

• The phenomenon of sea-level rise contributes to an elevated probability of coastal erosion and slope instability (Durap et al., 2022).

• Earthquakes have the potential to induce landslides in coastal environments, particularly in places characterised by high tectonic activity(Udo et al., 2012).

The mechanisms behind coastal flow slides.

• Coastal slope failure can take place as a consequence of many circumstances, including the presence of weak soil or rock strata, pronounced inclinations, and increased pore water pressure (van Rhee, 2015).

• Submarine slumping refers to the occurrence of underwater landslides that manifest along the seabed, leading to the rapid downslope flow of sediments (Lo et al., 2023).

Potential Impacts of Coastal Flow Slides:

Coastal flow slides have the potential to cause significant harm to many forms of infrastructure situated in coastal areas, including but not limited to houses, roads, bridges, and other essential structures (Durap et al., 2023).

- Loss of life: These occurrences have the potential to provide a substantial hazard to human life, especially when densely populated regions are impacted (Beinssen et al., 2015).
- Coastal erosion: Along with coastal flow slides play a significant role, resulting in the depletion of valuable land, beaches, and coastal ecosystems(van Rijn, 2011).
- The transportation of sediment: Flow slides have the capacity to carry significant quantities of silt into coastal seas, hence exerting an impact on water quality, marine habitats, and navigation channels (Durap et al., 2023).

- Tsunamis and seiches may pose additional hazards to coastal populations, since they can be generated by coastal flow slides under certain circumstances (Shimozono et al., 2016).

G. Van den Ham et al. 2014 proposed a criteria-based evaluation of coastal flow slides. Nevertheless, this approach is limited because it does not account for several important factors. These factors include dredging rate, number of coastal build-ings, coastal slope, packing type, driving forces, and so on. In addition, the suggested method does not have anything that sets it apart, therefore it implies an equal likeli-hood of flow slide breaching and liquefaction. Assumptions underpin the methodology as well, which may not be reflective of the complexities of coastal flow slides. In addi-tion, the suggested technique does not ensure that liquefaction, rather than breaching, would occur, which may have major ramifications for risk evaluation and mitigation plans.

Sassa and Takagawa, 2019 presented a stochastic evaluation of static liquefaction in a predominantly dilative sand fill [39]. The study used statistical methods to analyze the variability of soil properties and their impact on the liquefaction potential. The authors found that the critical state friction angle was the most significant factor af-fecting the probability of liquefaction. They also compared the results of the stochastic analysis with deterministic methods and found that the stochastic approach provided a more realistic and reliable assessment of the liquefaction potential. Overall, the study provided insights into the behavior of predominantly dilative sand fills under static loading conditions and highlighted the importance of considering uncertainty in soil properties in the assessment of liquefaction potential. The method for assessing land-slides in marine environments has proven to be a useful tool for predicting and man-aging potential landslides. However, like any method, there are limitations to its ap-plication. One of the primary drawbacks of this approach is that it does not account for coastal flow slides. Coastal flow slides are a specific type of landslide that occurs on slopes near the coastline and is characterized by the movement of material in a flu-id-like manner.

Additionally, there are several critical factors that this method does not take into consideration. For example, factors such as dredging rate, the number of buildings lo-cated along the coast, coastal slope, packing type, and driving forces, all have a signif-icant impact on the likelihood and severity of landslides in marine environments. Ne-glecting these critical factors can lead to underestimating the potential risk and impact of landslides in the area.

Furthermore, while the method for liquefaction was useful for identifying potential areas of liquefaction, it did not consider all coastal flow parameters. The coastal flow slide parameters are critical parameters that can significantly impact the severity and extent of liquefaction. Neglecting these parameters can lead to a misinterpretation of the risk of liquefaction in the area.

Lastly, the method did not label the parameters in terms of posing a danger for liquefaction. Without labeling the parameters in terms of posing a danger for liquefac-tion, it can be challenging to determine the level of risk associated with each parame-ter. Overall, while the method for assessing landslides in marine environments was useful, it is essential to recognize its limitations and take into account additional critical factors to accurately predict and manage potential landslides in the area.

Stoutjesdijk et al., 1998 discussed a method for predicting flow-slides on slopes based on slope geometry. The study examined the relationship between the geometry of the slope and the likelihood of flow-slides. The paper provided a detailed ex-planation of the flow-slide prediction method, including the critical geometry that af-fects flow-slide initiation and the corresponding mathematical equations.

The study involved examining data from several flow-slide events that occurred on different slopes to determine the critical slope geometry parameters that influence flow-slide initiation. The researchers analyzed the data using statistical methods to identify the critical slope geometry parameters and developed mathematical equations for predicting flow-slides based on these parameters.

The paper concluded that the flow-slide prediction method based on slope geometry was a useful tool for predicting flow-slides and could provide valuable information for managing potential flow-slide hazards. The paper focused solely on the influence of slope geometry on flow-slide prediction, and it did not consider other factors that could influence flow-slides, such as dredging rate, number of coastal buildings, coastal slope, packing type, and driving forces. Moreover, coastal flow slides can effect from soil type, vegetation, earthquackes, sea level rise, tide effect, wave height. Therefore, the weakness of the paper was that it provided a limited understanding of flow-slide prediction, as it only focused on one aspect of the problem, which was geometry, and neglected other critical factors that could significantly impact flow-slide initiation and propagation.

Furthermore, the suggested methodology lacks a discernible characteristic that differentiates it from other assessment methodologies. The lack of distinctiveness suggests an equivalent probability of both flow slide breaching and liquefaction, perhaps leading to an inaccurate representation of real-world situations. Moreover, the technique is predicated upon certain assumptions that may not comprehensively encompass the subtleties and complexity inherent in coastal flow slides.

Moreover, a notable limitation of this methodology is its inability to guarantee that liquefaction, as opposed to breaching, would be the probable result. The lack of attention to this matter may have substantial consequences for the evaluation of risks and the development of plans to minimise them, since these two situations need distinct techniques and responses.

Furthermore, the scope of this study is restricted to homogenous sandy slopes, hence limiting its capacity to capture the whole of sand-related settings. Hence, the findings obtained from this research may not possess general applicability across heterogeneous sandy terrains or varied geological contexts. The lack of variety seen in this research sample is a significant obstacle in generalising these results to a wider range of contexts.

It is essential to recognise that natural habitats possess a myriad of diverse and intricate characteristics. By limiting the study only to uniform sandy slopes, we unintentionally exclude crucial elements, discrepancies, and interplays that flourish in more diverse environments. The lack of attention to this aspect poses a potential danger of oversimplifying our understanding of the complex processes occurring on sandy slopes.

Hence, it is important to note that the recommendations and findings obtained from this research may not have direct relevance to practical scenarios characterised by diverse sand compositions or heterogeneous surroundings. The limitation indicated above limits the practical usefulness of the study's findings.

By focusing just on homogenous sandy slopes, there is a potential for adopting a limited viewpoint that overlooks the difficulties and unique qualities associated with different types of sand or mixed settings. The narrow scope of the inquiry restricts the range of this research.

Significantly, many fundamental elements pertaining to the behaviour of sandy slopes, such as erosion, stability, and other pertinent characteristics, may only manifest in heterogeneous or mixed sand settings. The potential omission of these circumstances in the research may result in the oversight of valuable possibilities to discover new insights or distinctive characteristics associated with different kinds of sand. These insights possess potential utility in several applications, including but not limited to environmental management and engineering.

Moreover, the use of the findings from the research for the development of models or forecasts may lead to a compromise in their accuracy when portraying real-world settings, particularly if these models simply depend on homogenous sandy slopes. The presence of this difference has the potential to result in inaccurate forecasts and misdirected suggestions.

Thus, further studies are required to provide more thorough and precise methodologies for evaluating and forecasting coastal flow slides. Therefore, in this study, sensitivity index was devised in section 4.2.

2.3 Bayesian Network

Bayesian Networks have been recognised as important instruments for the prediction and comprehension of coastal erosion and coastal flow slides dynamics(Uusitalo, 2007).

The use of Bayesian network modelling has gained momentum in the field of coastal research due to its potential to enhance results. This modelling approach is well-suited for generating statistical and probabilistic assessments of trends in coastal development (Poelhekke et al., 2016a).

In the field of coastal science, Bayesian networks have been increasingly used in many applications, such as the analysis of cliffs and landslides, as well as the assessment of groundwater flow. These applications are closely linked to the study of coastal bluff dynamics (Poelhekke et al., 2016b).

The effective use of Bayesian networks by the US Geological Survey in coastal areas, namely the Atlantic and Pacific coastlines, has resulted in improved predictions of coastal change. This improvement is achieved by integrating a priori knowledge of physical conditions, regulating mechanisms, and historical erosion rates into their modelling approach (Cooper et al., 1992; Gutierrez et al., 2011).

The advancement in computational capabilities and the increased accessibility of extensive datasets pertaining to coastal systems have facilitated the use of sophisticated data analysis techniques. These approaches enable the assessment of non-linear and multivariate relationships, therefore enhancing our comprehension of coastal phenomena, including storm erosion(Cooper et al., 1992).

The Bayesian network has shown significant efficacy in the interpretation and modelling of coastal information. Bayesian networks facilitate the graphical representation of conditional relationships between variables, as well as the incorporation of replacement information from other variables to address missing observations. Several researchers, including (Gutierrez et al., 2011), and (van Verseveld et al., 2015), have employed Bayesian networks in their investigations to forecast erosion trends and patterns across various segments of the United States coastline. These studies consider various factors such as local sea-level rise rates, wave climate, and coastal geomorphology. Bayesian networks are very suitable for tackling coastal science challenges due to their capacity to provide statistical and probabilistic estimations (Namazian et al., 2019). These networks have the capability to analyse several factors and their interconnections, enabling researchers to assess complex interactions that may impact coastal erosion and coastal flow slides.

Several studies have utilized Bayesian networks to address a range of challenges in coastal science and management, as summarized in Table 2.1.

Table 2.1: Research scope, study area, data origins, and variables.

Challenges	Related works	Study area	Objectives
Modeling storm surge risk and impact	Classifying compound coastal storm and heavy rainfall events in the north-western Spanish Mediterranean (Marc Sanuy et al., 2021)	North-east of the Iberian Peninsula, Catalonia	Researchers used Bayesian networks to combine historical data, storm surge models, and expert knowledge to estimate the probability of flooding in coastal areas.
Assessing the vulnerability of coastal ecosystems to climate change	A Bayesian network to predict coastal vulnerability to sea level rise (Gutierrez et al., 2011)	Atlantic coast, US	BN was used to characterize the connections between the Atlantic coast of the United States and its driving factors, geologic limitations, and coastal reaction. This definition includes local rates of relative sea level rise, wave height, tide range, geomorphic categorization, coastal slope, and shoreline change rate measurements.
Optimizing management decisions for coastal resources	A Bayesian network approach for coastal risk analysis and decision making (Jäger et al., 2018).	The North Norfolk coast, England	Bayesian networks were employed to evaluate and prioritize flood management options based on their probabilistic effectiveness in achieving desired outcomes.

Bayesian network formulae provide a mathematical framework that facilitates the modelling and analysis of uncertain interactions among variables. Those equations, which are derived from Bayes' theorem, enable us to make estimations about the likelihood of an event or variable by using preexisting knowledge and observable information. The Bayes formula, which serves as the fundamental basis for Bayesian network formulae, is a very effective technique for the computation of posterior probabilities (Qiu et al., 2020). The Bayesian network is composed of nodes, directed connections, conditional probabilities associated with nodes, and a directed acyclic graph ((Jiang et al., 2021)

The precise expression of the likelihood of event A happening, given the occurrence of event B, may be achieved by the use of the Bayesian formula. The Bayesian network offers a systematic approach for representing and analysing uncertain correlations among variables.

Conceptualizing the Theorem:

- Prior Probability (P(A)): This represents the initial belief in the occurrence of event A, absent any additional evidence. It signifies degree of conviction before new information surfaces.
- Likelihood (P(E|A)): This depicts the probability of observing evidence E under the assumption that event A is true. It quantifies how likely the evidence is, given the truth of the hypothesis.
- Posterior Probability (P(A|E)): This is the crux of Bayes' theorem – the updated belief in event A after considering evidence E. It reflects how the evidence has shifted the study’s initial belief, potentially reinforcing or weakening it.

Mathematical formulation:

$$P(A|E) = \frac{P(E|A) * P(A)}{P(E)} \tag{2.1}$$

P(A|E): Posterior probability of event A given evidence E.

P(E|A): Likelihood of evidence E given event A.

P(A): Prior probability of event A.

P(E): Total probability of observing evidence E (considering all possible events that could lead to it).

The Bayesian network is a visual depiction of information that facilitates the process of making inferences in situations characterised by uncertainty (Namazian et al., 2019). Decision analysis is a very effective technique that facilitates the examination of decisions by providing capabilities for prior analysis, posterior analysis, and pre-posterior analysis (Figure 2.3).

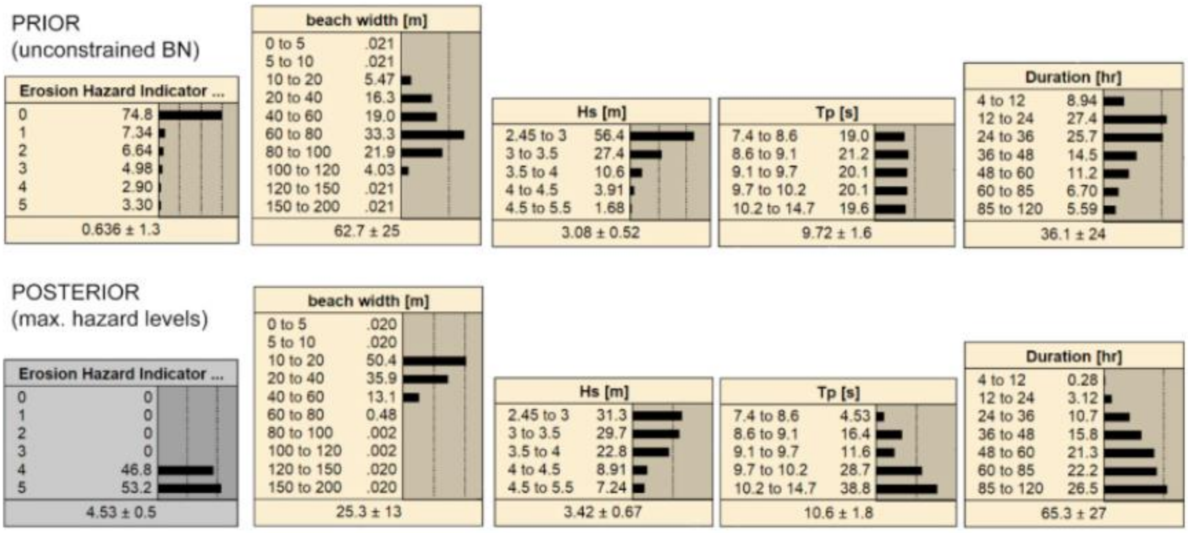


Figure 2.3: Findings from the identification of the danger source at Malgrat North (M. Sanuy et al., 2020).

3. METHODOLOGY

This research adopts a comprehensive methodology to delve into the dynamics and mechanics of coastal flow slides (CFS), a critical geological phenomenon affecting coastal regions. By weaving together laboratory experiments, field data collection, and sophisticated computational modeling, this study aims to unravel the complexities of CFS. The ultimate goal is to enhance our understanding of these events, thereby facilitating improved risk assessment and the development of effective mitigation strategies for coastal areas.

At the heart of this methodology is the integration of diverse research approaches, each playing a pivotal role in achieving a holistic understanding of CFS. Laboratory experiments allow for the controlled observation and analysis of the physical processes underpinning flow slides, offering valuable insights into their mechanics. Field data collection, on the other hand, provides real-world context, enabling the validation of laboratory findings and computational models against actual events. Computational modeling serves as the bridge between theoretical knowledge and practical application, allowing for the simulation of complex scenarios that are difficult or impossible to replicate in a laboratory setting.

A key aspect of this research is the focus on the mechanism of CFS, illustrated in Figure 3.1. This figure depicts the gravity-driven flow of sand from the retrogressing front, a process that initiates and sustains sediment transfer. The transported sand then accumulates in areas with moderate slopes, highlighting the dynamic nature of sediment redistribution during a flow slide event. Understanding this mechanism is crucial for predicting the behavior of CFS and for designing effective coastal management and engineering solutions.

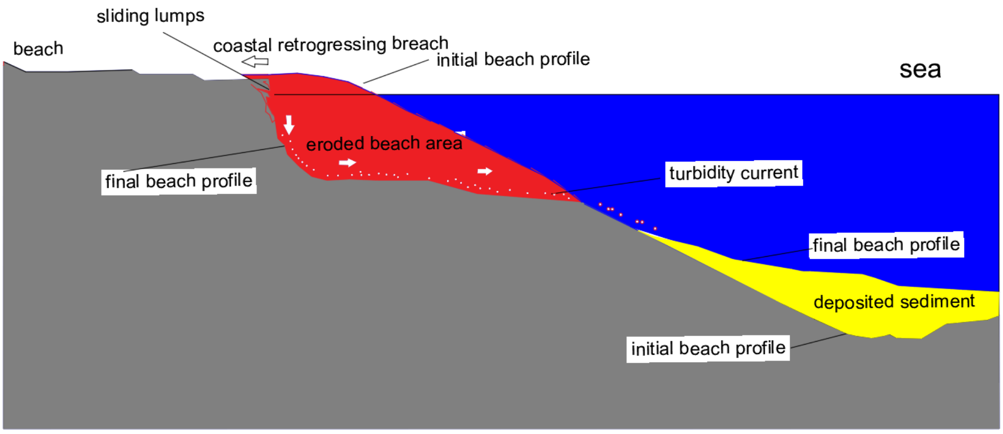


Figure 3.1 : Schematic representation of coastal flow slides

Given the critical importance of understanding the gravity-driven flow mechanism of CFS for effective coastal management, this research extends beyond theoretical analysis to include a holistic approach that combines laboratory experiments, field observations, and advanced computational modeling to address the multifaceted nature of CFS phenomena.

- Laboratory Experiments: Involved the collection and preparation of sand samples from various sources, ensuring they represent natural deposits accurately. Experiments included sieve analysis for sediment characterization, breach height and velocity experiments to simulate coastal flow slide scenarios, hydraulic conductivity testing to evaluate sediment permeability, and tilting box experiments for friction angle analysis.

- Field Data Collection: Conducted site inspections to gather real-world data related to coastal flow slides, including current velocity, tide levels, and groundwater levels.

- Computational Modeling: Utilized Bayesian Networks for probabilistic risk assessment, and sensitivity analysis to evaluate environmental factors' impact on coastal regions.

This research utilized a holistic approach combining field observations with laboratory experiments to understand the complex dynamics leading to CFS. The study at Amity Point served as a prime example of integrating real-world conditions with controlled experiments to gain a comprehensive understanding of the factors contributing to CFS. By addressing high tide fluctuations, groundwater level changes, hydraulic gradients, sediment accumulation, slope, compaction, and specific soil characteristics, this research provides valuable insights into coastal geomorphology and stability. These findings are instrumental in developing predictive models and effective mitigation strategies for coastal flow slides, contributing significantly to coastal management and preservation efforts.

This study was achieved through the following steps:

Data collection procedures

Data collection involved meticulous selection and preparation of sand samples, execution of controlled laboratory experiments to simulate and analyze coastal flow slide phenomena, and site inspections for real-world data collection. Advanced modeling techniques were applied to integrate findings from experiments and field data into comprehensive risk assessment models.

High tide fluctuations and site selection

The selection of Amity Point on North Stradbroke Island was due to its history with Coastal Flow Slides (CFS) and significant high tide fluctuations. Measurements at Amity Point and data from the Queensland meteorological station provided a dual approach for analyzing tide range fluctuations, crucial for understanding coastal dynamics and the potential for CFS occurrences.

Groundwater level fluctuations

Groundwater wells placed strategically in the study area measured how high tides influence groundwater levels, creating hydraulic gradient differences. This fluctuation is vital for understanding conditions leading to CFS events, highlighting the interplay between tides, groundwater, and coastal stability.

Hydraulic gradient differences

A comprehensive approach through site inspections and tilting box experiments explored hydraulic gradient differences. Site inspections monitored changes in groundwater levels, while tilting box experiments simulated these differences in a controlled setting, providing insights into the hydraulic gradients' role in CFS.

Sediment accumulation and slope

Investigations into sediment accumulation and slope were conducted through site inspections and tilting box experimental studies. These approaches aimed to understand how sediment accumulation leads to steep slope formations, a critical factor in CFS initiation.

Compaction

The impact of soil compaction on CFS was studied through site inspections and laboratory experiments, including tilting box and hydraulic conductivity studies. Compaction tests varied the number of taps to simulate different compaction levels, exploring their influence on CFS likelihood.

Specific soil characteristics

Critical soil characteristics such as soil shape diversity, hydraulic conductivity variations, and the angle of internal friction in dry and wet conditions were examined through laboratory tests. These characteristics are crucial for predicting potential CFS and for implementing effective coastal management strategies.

Angle of internal friction

The angle of internal friction was evaluated through tilting box experiments, measuring the angle of sliding failure under different conditions. This angle is pivotal for understanding soil stability and resistance to shear stress, which determines the resilience of soils to environmental stresses.

Significant wave height (SWH)

Wave action can lead to soil saturation in coastal regions. High values of significant wave heights increase the likelihood of soil saturation, thereby increasing its susceptibility to failure. Data of SWH can be utilised for evaluating the coastal flow slides vulnerability in coastal regions with high levels of saturation.

The prediction of significant wave height can be used to estimate the variations in pore pressure within the coastal slope. Waves can induce cyclic changes in pore pressure, known as pore pressure pulsing, which can weaken the soil and reduce its shear strength. This is particularly relevant in fine-grained soils where changes in pore pressure can significantly affect slope stability.

The prediction of significant wave height, in conjunction with other factors like groundwater levels, low tide levels, sediment accumulation, and coastal slope steepness, can be used comprehensively in the risk assessment of coastal flow slides. When high significant wave height brings more sediment to the shore, creates a steep coastal slope, and coincides with high groundwater levels and low tide conditions, it can contribute significantly to landslide risk assessment in the following ways:

- High significant wave heights are often linked to greater wave energy, resulting in the transportation and deposition of substantial sediment quantities throughout coastal regions. The accumulation of sediment at the base of the coastal slope can increase the weight and instability of the slope. Consequently, the size of coastal flow slides, as measured by event size (m^2), can increase significantly.
- The combination of high groundwater levels, low tide, and steep coastal slopes can create a high hydraulic gradient along the slope. This means that groundwater will flow more rapidly and potentially induce higher pore pressures within the soil mass, further reducing slope stability.

Bayesian network for probabilistic risk assessment

In this research, it was harnessed a Bayesian Network (BN) as a sophisticated statistical model to conduct a probabilistic risk assessment of factors contributing to coastal flow slides (CFS). This approach is pivotal for understanding the complex and dynamic nature of coastal hazards, enabling a holistic and precise evaluation.

After meticulously analyzing interactions between high tide fluctuations, groundwater level changes, hydraulic gradients, sediment accumulation, slope, compaction, and specific soil characteristics, we establish the BN as a culmination of this thesis findings. The BN serves as a nexus, consolidating insights from laboratory experiments, field data, and computational modeling to assess the joint probability of various factors influencing CFS. This comprehensive risk assessment underscores the multifaceted nature of coastal hazards and contributes to both academic discourse and practical insights for coastal management and hazard mitigation strategies.

Integrating advanced modeling techniques:

This research represents a significant advancement in coastal flow slide risk assessment. By combining sensitivity analysis, sensitivity index, Bayesian Networks, experimental study, and site inspection, this study offers a comprehensive, data-driven perspective. This methodology is particularly relevant in the context of changing environmental conditions, including the challenges posed by climate change. It provides a robust framework for understanding and mitigating the risks of coastal flow slides, aiding in the development of sustainable and effective coastal management strategies.

Justification of choices and alignment with research questions

The choice of integrating laboratory experiments with field data collection and computational modeling is justified by the complex nature of coastal flow slides, which requires a holistic understanding of various contributing factors. This methodology aligns with the research questions by:

- Providing a comprehensive analysis of the factors contributing to coastal flow slides.
- Enabling the prediction and assessment of risks associated with coastal flow slides.
- Facilitating the development of effective risk mitigation and management strategies for coastal regions.

The use of advanced computational models like Bayesian Networks and Sensitivity Index development is justified by the need for accurate prediction and assessment tools that can handle the complexity and variability of environmental factors impacting coastal flow slides.

Sensitivity index in coastal flow slide analysis

The sensitivity index is pivotal in this study, used alongside Bayesian Networks, on-site inspection, experimental study alongside sensitivity index. The primary goal of this thesis is to conduct a sensitivity analysis to evaluate how coastal regions react to various environmental factors. This holistic approach employs probabilistic methods to assess the effects of variability in input parameters on the overall risk posed by coastal flow slides. It aids in quantifying uncertainty and understanding the potential range of outcomes under different scenarios.

3.1 Experimental and Site Inspection of Coastal Flow Slide

3.1.1 Sample collection and preparation

The initial phase of this experimental setup involved the meticulous collection of sand samples from distinct locations at Amity Point. This collection process was carried out in two separate phases; the first set of samples was obtained on 14 November 2022, and the subsequent collection occurred on 10 January 2023 (Figure 3.2). Each collection phase targeted different locations to ensure a diverse range of samples, reflecting the varied grain sizes naturally present at Amity Point. The purpose behind this methodical sampling was to capture the heterogeneity of the sand at Amity Point, which is crucial for understanding the specific conditions under which flow slides occur.

Subsequently, the samples were subjected to a meticulous drying proceeding to eliminate any residual moisture that could potentially introduce bias into the study. The experimentation was meticulously executed within a rigorously controlled environment, safeguarding the integrity of the samples throughout the process.

After the completion of the drying procedure, the samples were subjected to sifting in order to eliminate any sizable aggregates or contaminants that may have been present. The careful and thorough process ensured that only the most refined variant of each sand type was separated for comprehensive analysis and assessment.

A rigorous and systematic approach underpinned the subsequent studies, employing meticulously constructed scenarios that mirrored the natural sand deposits. This methodology facilitated a thorough understanding of the unique experimental outcomes and intrinsic qualities exhibited by each sand variant.

To further diversify through experimental setup and enhance the comparability of this study results, it was acquired six different materials with varying mean diameters. This selection included a range of sands and glass beads, each chosen for their distinct grain sizes. These materials comprised Mineral Sand, Amity Point Beach Sand (APBS), Medium Grained Sand, and Coarse Grained Sand (Figure 3.3), alongside two types of glass beads—Pink Glass Bead and White Glass Bead. The inclusion of these materials allowed for a comprehensive examination of grain size effects on the physical behaviors of interest, particularly regarding flow slides and sand retreat mechanisms.

The preparation of the collected sand samples and the acquired materials was followed by a series of characterizations to determine their physical properties. Central to this characterization was the determination of the grain size distribution for each sample, for which sieve testing was employed. The sieve testing results were meticulously plotted to obtain the d50 grain size, a critical parameter for understanding the sediment dynamics under study.

In addition to grain size distribution, the samples underwent further testing to assess their hydraulic conductivity, solids fraction, friction angle under both wet and dry conditions, and compaction characteristics. These tests were instrumental in identifying the geo-mechanical and hydrological parameters that influence sand behavior, particularly the rate of sand retreat from a vertical face. The friction angle testing, for instance, included tilting box experiments conducted under varying moisture conditions to simulate breaching events. This approach not only provided insights into the factors affecting sand retreat but also enhanced the repeatability and reliability of experimental observations through the consideration of potential errors.

Figure 3.2 : Amity point sand sample collection**.**

Figure 3.3 : Several sorts of sand that were used in the experimental investigation.

An integral part of understanding sediment characteristics is analyzing their grain size distribution, which was accomplished through sieve analysis, as explained next.

3.1.2 Sieve analysis

The particle size distribution of the sediment samples was determined using sieve analysis conducted at the Geotechnical Laboratory of University of Queensland. This analysis involved passing the sediment samples through a series of sieves with progressively smaller mesh sizes to separate particles based on size. The outcomes of the sieve analysis provided crucial data on the sediment's composition, aiding in the understanding of its mechanical properties and response to various loading conditions. These results served as a foundational basis for subsequent examinations and evaluations.

With a comprehensive understanding of the sediment properties, we then focused on simulating actual coastal flow slide scenarios, as detailed in the breach height and velocity experiments.

3.1.3 Breach height and breach velocity experiments

The breach height and velocity experiments aimed to simulate coastal flow slide scenarios and understand their dynamics. The experiments involved the controlled release of sediment and water from a breach point. Specifically, four different sand materials were used to study the retreating velocity, and each material underwent testing to measure its density, porosity, and grain diameter. The experiment measuring the retreating velocity utilized a gridded rectangular box filled with sand and fluid, which was tilted from horizontal to vertical. The rate at which the sand collapsed was recorded, providing insights into the behavior of coastal flow slides under varying conditions.

Furthermore, the experiments encompassed eight different scenarios, involving the use of two different fluids alongside the four sand materials. Additionally, 65 experimental studies were conducted using water, Amity Point Sand, and Heavy material in various configurations of the tilting box experiment (Figure 3.4). These configurations included different faces of the tilting box, such as the 24 cm face and the 40 cm face, as well as variations in the speed of tilting, slope, and elapsed time for full tilting.

Figure 3.4: Tilting box experiments under different scenarios of sand, fluids, and tilting speed.

To further our understanding of sediment behavior, especially in terms of conductivity, hydraulic conductivity tests were conducted, as elaborated in the following section.

3.1.4 Hydraulic conductivity testing

Hydraulic conductivity measurements were performed to evaluate the porousness of coastal sediments (Figure 3.5). The fluid transmission through the sediment was measured. The sediment samples were subjected to a hydraulic gradient using a constant head permeameter. Over time, the water velocity through the samples was tracked. The results of these experiments are important because they provide light on the ease with which fluids might penetrate and possibly set off coastal flow slides in various sediment types.

Specialised testing equipment was carefully designed and constructed in order to accurately determine the hydraulic conductivity of the sand samples. The design of this equipment was executed with meticulous attention to detail, including several essential elements in order to guarantee precise and reproducible measurements. The testing equipment comprises the following components:

The central component of the device consists of a long and slender vertical tube, which is outfitted with a painstakingly engineered filter positioned at its lower end. The use of this filter is crucial in effectively avoiding the escape of sand particles, while simultaneously facilitating the permeation of water.

Two smaller tubes were strategically affixed at regular intervals of 50 centimetres along the length of the main vertical tube for the purpose of measuring water levels. This configuration enables accurate quantification of water levels at various locations within the system.

A hose was attached at the uppermost part of the equipment to provide regulated water flow. This particular component facilitates the control of the water flow rate, which is a crucial element in the measurement of hydraulic conductivity.

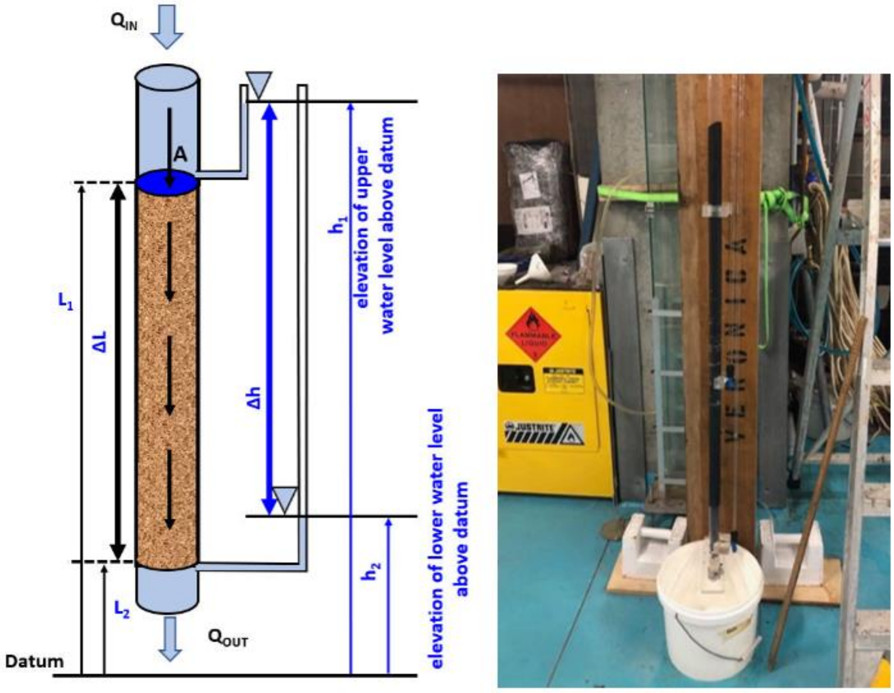


Figure 3.5 : Hydraulic conductivity tests.

Alongside the device itself, a set of essential factors were meticulously monitored in order to precisely determine the hydraulic conductivity of the sand samples. The variables that are essential components of the hydraulic conductivity equation are as follows:

$$K = \frac{Q/A}{\frac{h_1-h_2}{L}} \qquad (3.1)$$

where:

- K is the hydraulic conductivity, in units of cm/s
- Q is the flow rate of water through the sand, in units of mL/s
- A is the cross-sectional area of the main tube, in units of cm^2
- h_1 is the height of water in the first tube plus the height difference between the two tubes, in units of cm
- h_2 is the height of water in the second/lower tube, in units of cm
- L is the height of the sand in the main tube, in units of cm

Building on the understanding of sediment permeability, the research progressed to examining the mechanical stability of these sediments. This was achieved through tilting box experiments, as detailed in the next section.

3.1.5 Tilting box experiments and friction angle analysis

Tilting box experiments were performed to determine the friction angles of coastal sediments (Figure 3.6). A tilting box apparatus was inclined incrementally until the sediment within it began to move. By measuring the critical angle of inclination, we obtained valuable data on the internal friction characteristics of the sediment. These experiments are crucial for assessing the stability of coastal slopes and the potential for flow slides.

Prior to initiating the testing of the fluid-grain combination, a set of tests with tilting boxes was conducted to determine the velocity at which sand retreats from a vertical surface, thereby successfully replicating a breaching event.

The conducted studies included many factors, including the tilt degree, initial packing density, and particle size distribution. The use of this complete methodology enabled a detailed examination of the manner in which these elements impact the behaviour of sand in the event of a breach.

The influence of tilt angle and initial packing density on breaching velocity in granular media was investigated through a series of meticulously controlled experiments. By systematically manipulating the tilt angle, it was possible to elucidate the critical angles at which breaching events are most likely to occur. Additionally, the impact of initial compaction on the behavior of the granular substrate under breaching conditions was assessed by examining various packing densities. This comprehensive analysis yielded valuable insights into the complex interplay between these factors and their combined effect on breaching velocity.

Figure 3.6 : Tilting box experiments to fathom critical angle slope.

Moreover, the experiments took into account the particle size distribution of the sand. The comprehension of how the flow dynamics of a sand mixture during a breaching event might be influenced is contingent upon the study of this crucial element. Through a rigorous examination of the intricate relationship among these factors, a more complete comprehension of breaching phenomena was attained, hence providing useful empirical evidence for further research endeavours and engineering implementations.

The determination of the friction angle of granular materials in various settings, including water and silicone oil, was conducted by a systematic experimental approach followed by a comprehensive analysis (Figure 3.7). This undertaking was of utmost importance in yielding significant observations on the mechanical response of granular materials under different circumstances.

The friction angle (φ) formula was used to calculate friction angle.

$$\tan(\phi) = \frac{\delta}{h} \tag{3.2}$$

φ is friciton angle,

δ is the horizontal displacement,

h is the height of the specimen.

Figure 3.7 : Friction angle determination for different sort of sand.

Tilting box experiments were conducted to assess the friction angles of sandy materials, providing essential insights for understanding the stability of coastal slopes and the dynamics of potential flow slides. The core of the experiment involved a rectangular glass box, which was incrementally tilted until the sand within exhibited sliding failure. This setup allowed for precise measurement of the angle at which movement commenced, shedding light on the internal friction characteristics of the sediment.

A significant aspect of the methodology was the deliberate alteration of geo-mechanical and hydrological parameters, such as sand compaction and saturation levels, to evaluate their impact on the friction angle. This was crucial for understanding the complex interplay between these factors and their collective influence on sediment retreat and slope stability.

Compaction of the sand was achieved through a unique process known as tapping. Tapping involves gently striking the tilting box at specified intervals to compact the sand uniformly. For dry sand, this compaction was methodically executed with a series of taps at intervals of 1, 3, 5, 10, 21, 41, 80, and 200 taps. For wet sand, the compaction process was adapted to fewer taps, with intervals of 1, 3, 5, 10, 20, and 50 taps. This tapping technique is instrumental in gradually increasing the density of the sand, ensuring a uniform compaction throughout the experiment. It simulates natural sedimentary processes that compact materials over time, providing a controlled way to study the effects of compaction on the friction angle.

Initial experiments concentrated on the behavior of uncompacted sand to establish a baseline for friction angles. Subsequent experiments involved the compacted sand, repeating the tests to observe how compaction affects the friction angle. To explore the role of moisture, experiments were also conducted with saturated sand, determining the wet friction angle and illustrating the impact of water on sand behavior.

By systematically varying the sand's physical state and environmental conditions within the tilting box—through adjustments in tilt degree, compaction level, and moisture content—the experiments offered a comprehensive examination of the variables affecting sediment behavior during a breach. This approach enabled a detailed analysis of how these factors influence sand behavior, providing valuable insights into slope stability and sediment movement in coastal environments.

Throughout the experimental phase, a range of configurations (Table 3.1) and setups were used in order to precisely quantify the friction angle. Specialized equipment was used to deliberately create controlled stress and deformation inside the granular material samples. The studies were done with great attention to detail in order to guarantee the capacity to reproduce the findings and assure the dependability of the results.

Table 3.1: The first three experimental configurations for tilting box in 65 tests.

Experiment no	Mean particle size (D50) (mm)	Slope (m/m)	Specific gravity of material (g/cm3)	Elapsed time for fully tilting (s)	Tilting box speed (m/s)	Breach height (m)	Breach velocity (m/s)
1	0.215	10.7	2.65	1.88	0.128	0.0781	0.00416
2	0.215	11.02	2.65	1.78	0.135	0.0826	0.00427
3	0.215	11.79	2.65	1.60	0.150	0.0931	0.0045

After conducting the experiments, a comprehensive analysis was carried out. The task consisted of the analysis and interpretation of the data acquired via the conducted experiments. In this study, several statistical approaches, regression analysis, and mathematical models were used to derive significant findings pertaining to the behaviour of granular materials in aqueous and silicone oil environments.

The investigation further included a comparative examination of the friction angles recorded in water and silicone oil. This comparative analysis has provided deeper insights into how the choice of fluid medium can significantly influence the mechanical behavior of granular materials. The measured friction angles were notably influenced by factors such as fluid viscosity, density, and intermolecular forces.

Moreover, the consequences of these discoveries were thoroughly evaluated. The comprehension of the friction angle shown by granular materials in diverse settings has significant implications throughout several fields, including geotechnical engineering and environmental sciences. The information acquired via these experiments and analysis may be used in the development of architectural frameworks, evaluation of landslides, and other geotechnical applications.

To further explore sediment behavior, particularly under conditions that mimic natural environments, we integrated fluid dynamics into the tilting box experiments, as described in the following section.

3.1.6 Fluid-grain mixture testing

Building upon the investigations sample collection and preparation, a series of tests were carried out to examine fluid-grain mixtures. The studies conducted in this study replicated real-world scenarios by adding fluids, which served as agents for oil silicione and freshwater, into the sediment. The observation was conducted on the behaviour of the sediment-fluid combination while the tilt angles were varied. This enabled us to get insights into the impact of fluid presence on the stability of coastal sediments and their vulnerability to flow slides.

The selection of these parameters was made in order to conduct a complete investigation of the behaviour of fluid-grain mixes across a range of situations and settings. The primary objective was to acquire a more profound comprehension of their natural features and corresponding reactions. The primary factors and variables taken into account were as follows:

- The grain density, denoting the mass per unit volume of the solid grains, was determined by carefully measuring the volume of a known weight of grains using a graduated cylinder. This volume and weight method involved ensuring consistent packing density to minimize air gaps and improve accuracy. Throughout the experimental procedures, the grain density was carefully regulated by using this method to monitor and adjust the amount of grains added to the mixture, ensuring consistent overall density and packing properties. This parameter has significant importance as it exerts a direct impact on the overall density and packing properties of the mixture.

- The study carefully chose a variety of volume fractions to investigate the impact of the percentage of solid grains to the overall volume of the mixture on its behaviour. This measure facilitates the identification of pivotal thresholds at which the parameters of the mixture undergo substantial changes.
- The particle size distribution of the solid grains was carefully examined and documented (Figure 5.1). It is important to comprehend the influence of various grain size distributions on the flow behaviour of a mixture, since this knowledge is crucial for both theoretical comprehension and real-world implementations.
- The fluid dynamic viscosity, a critical parameter for assessing resistance during the flow of a mixture, was meticulously regulated and quantified through precision control and measurement techniques. Understanding the dynamic viscosity is crucial for analyzing the level of resistance a mixture encounters as it flows, significantly influencing the transport and behavior of the mixture in various contexts. In the study of coastal flow slides, the viscosities of water and silicone oil, both of which are well-documented, are of particular interest. By examining the known dynamic viscosities of these substances, we can gain insights into their effects on coastal flow slides. The precise measurement and control of dynamic viscosity allow for a detailed examination of how these fluids interact with coastal sediments, potentially altering the flow dynamics and stability of coastal slopes. This understanding is essential for predicting and mitigating the impacts of coastal flow slides, which can have profound effects on coastal environments and human settlements.
- The investigation included the measurement of the retreating velocity, which serves as a significant parameter for assessing the movement and behaviour of fluid-grain mixtures, across various fluid types. This parameter facilitates the evaluation of how fluid qualities influence the overall dynamics of the mixture.

Through meticulous definition and manipulation of the experimental settings and circumstances, a thorough investigation of the behaviour of fluid-grain mixtures was successfully conducted. The use of this methodical methodology for a comprehensive examination of the intricate interaction between the solid particles and the liquid component, yielding significant observations applicable to a wide range of fields including environmental research, engineering design, and hazard evaluation.

To further our understanding of sediment behavior, especially in terms of compaction, solid fraction tests were conducted, as elaborated in the following section.

3.1.7 Solid fraction test

Solid fraction tests were carried out on sediment samples using four different types of sands. Both wet and dry conditions were considered. Tapping from the top of the tilting box was used to compact the sand within the box and determine solid fraction. This allowed us to investigate the compaction behavior of coastal sediments, which is critical for assessing their stability.

The relationship between hydraulic conductivity and solid fraction was then explored to understand how these factors interplay in affecting sediment permeability, as detailed next.

3.1.8 Hydraulic conductivity vs. solid fraction test

Building upon the hydraulic conductivity tests, a comprehensive analysis was conducted to establish the relationship between hydraulic conductivity and solid fraction. Four different types of sands were used in this analysis, both in wet and dry conditions. This investigation aimed to uncover how solid fraction influences the permeability of coastal sediments and, consequently, their susceptibility to flow slides.

To complement laboratory findings with real-world data, site inspections were conducted, as described in the next section.

3.1.9 Site inspection measurments

Comprehensive field investigations were conducted at Amity Point to gather real-world data on coastal flow slides. Key environmental parameters were measured, including current velocity, tide levels, and groundwater levels (Figure 3.8).

Current velocity measurements:

Current velocities were acquired utilizing a simple yet effective method. A wooden branch was deployed from the deck structure at a designated point of measurement and allowed to drift freely across the water surface. The time taken for the branch to traverse a predetermined distance between two fixed points on the deck was recorded using a timer. Measurements were performed at regular intervals of 15 minutes and meticulously documented in a dedicated notebook, ensuring data integrity.

Groundwater level measurements:

Groundwater levels were assessed using established monitoring wells strategically positioned within the study area. A leveling instrument facilitated precise measurements at 15-minute intervals, adhering to the same temporal schedule as the current velocity measurements. This synchronized data collection enabled valuable insights into the potential interplay between groundwater dynamics and coastal flow slide activity.

Data analysis and interpretation:

The acquired data underwent rigorous analysis to illuminate the environmental factors potentially triggering or contributing to coastal flow slides at Amity Point. Statistical techniques and correlative studies were employed to establish relationships between the measured parameters and flow slide occurrences. These insights will contribute to a comprehensive understanding of the underlying mechanisms governing coastal flow slide events, ultimately aiding in developing effective mitigation strategies and safeguarding coastal communities.

Figure 3.8: Site inspection of CFS on Amity Point

Utilizing the data and insights gained from both laboratory experiments and field observations, we developed a sensitivity index for coastal flow slides, as explained below.

3.1.10 Physical modellling considerations, dynamics, and dimensional analysis

Along the vertical face, the downwards sediment transport rate should satisfy the conditions necessary to maintain geomorphological equilibrium within the system.

$$q_{s,z} = -q_{s,surface} + z(1 - p_d)\frac{dx_B}{dt} \text{for } z < 0 \tag{3.3}$$

The initial term in the given equation accounts for the erosion processes occurring above the aquatic interface, designated by the notation (z=0), highlighting the air-water boundary's significance in sediment dynamics. This term plays a crucial role in understanding the erosional forces at play above sea level, contributing to the overall morphology of coastal and riverine landscapes.

The variable p_d represents the porosity of the sand within the vertical face, a critical parameter that influences the hydraulic conductivity and, consequently, the susceptibility of the sediment to erosion and transport. Porosity, in this context, not only affects the rate at which water infiltrates and flows through the sediment column but also has a profound impact on the stability of the slope and its resistance to erosional forces.

The sediment transport rate within the turbidity current, denoted as q_s [m^2/s], establishes a fundamental link between the geomorphological features of the landscape, such as the scarp and breach height (H_{scarp} +H_B)

$$-(H_B + H_{sarp})\frac{dx_B}{dt} = q_s \tag{3.4}$$

and the retreat rate of the erosional face. This relationship is pivotal in quantifying the dynamics of sediment movement and deposition in aquatic environments, providing insights into the processes that shape underwater landscapes and influence coastal erosion and sedimentation patterns.

The coupling of H_{scarp} +H_B with the retreat rate underscores the integral role of physical topography and the forces of erosion and deposition in determining the evolution of landforms. The scarp and breach height are not only indicative of the current state of erosion but also serve as predictors of future landscape changes, offering a window into the temporal dynamics of sediment transport and deposition.

$$\rho_w(s-1)g(1-p_d)\delta > \Delta_\mathrm{p}\tan\,\varphi \tag{3.5}$$

The shear stress generated by gravity (g) acting on the vertically sliding layer (thickness δ) must overcome friction-resistance generated by the dilation suction (Δp) and the friction angle (φ). This dynamic interplay determines the threshold at which the layer will initiate movement.

In this scenario, the dilation suction (Δp) is generated by the continuous process of gravity dragging downwards on the sliding surface layer of thickness δ. Simultaneously, the pore water deficit is relieved at a rate directly dependent on the hydraulic conductivity (k), a parameter controlling the ease of fluid flow through the material.

In a steady-state condition, the bed shear stress under the turbidity current is governed by principles of fluid dynamics and sediment transport, and can be expressed as:

$$\tau_\mathrm{b} = \rho_\mathrm{w}(s-1)g\frac{q_\mathrm{s}}{V} \tag{3.6}$$

where $\frac{q_s}{V}$ is the thickness of the solid grain, which is the thickness of the sediment in motion.

The retreat rate:

$$\boldsymbol{V}_\mathbf{B} = -\frac{\mathbf{d}\boldsymbol{x}_\mathbf{B}}{\mathbf{d}\boldsymbol{t}} \tag{3.7}$$

is depend on

The dilation potential β (dimensionless) ie, the difference between the critical (dilated) porosity and the densely packed porosity

β = pc-pd (3.8)

2. The thickness δ of the vertical layer being mobilised by gravity. This layer is assumed to be a certain number of grain diameters and hence scaling on the median grain size d50.

3. Buoyancy-reduced gravity (s-1)g

4. The hydraulic conductivity of the presumably densely packed material in the vertical face, say kd , and on the friction angle of the densely packed sand.

That is,

$$V_B = F(d_{50}, k_d, \beta, (s-1)g, \varphi_d) \tag{3.9}$$

$$V_B \propto \beta^{p1} \sqrt[3]{(s-1)gd_{50}k_d} \propto \beta^{p1} d_{50} \sqrt[3]{\frac{(s-1)g^2}{v}} \quad , \; \beta = p_c - p_d > 0 \tag{3.10}$$

3.1.11 Sensitivity index for coastal flow slides

A sensitivity index was established to quantify the vulnerability of coastal areas to flow slides. This index incorporated data from the previous sections, including hydraulic conductivity, friction angles, breach characteristics, and site-specific factors. The index aimed to provide a comprehensive assessment of the susceptibility of coastal regions to flow slides, aiding in hazard management.

Finally, to synthesize the findings of the study into a predictive framework, we employed Bayesian network modeling, as detailed in the final section.

3.1.12 Bayesian network modeling

The Bayesian network, also known as a Bayesian belief network or a probabilistic graphical model, is a visual depiction of the probabilistic connections between a group of variables. The system consists of interconnected nodes, directed linkages (edges), and conditional probabilities assigned to each node. The standard representation of the network is a directed acyclic graph (DAG), whereby the nodes symbolise random variables, and the edges symbolise probabilistic relationships among these variables (Figure 3.9).

The mathematical expression representing a Bayesian network may be succinctly described as follows:

Nodes (Vertices): In the context of a Bayesian network, it is important to note that each node corresponds to a distinct random variable.

Directed Links (Edges): Probabilistic dependencies between variables are represented by directed edges connecting the nodes in a network. Conditional probabilities are often used as a representation for these types of interdependence.

Conditional Probabilities: The conditional probability distributions of each node quantify the dependence of the probability of that node's value on the values of its parent nodes, which are nodes linked to it by incoming edges.

Directed Acyclic Graph (DAG): The graphical structure of a Bayesian network must be acyclic, indicating the absence of cycles within the network. The absence of cycles in this form guarantees the network's suitability for conducting efficient probabilistic inference.

The fundamental principle behind Bayesian network modelling relies on Bayes' theorem, which establishes a connection between conditional probabilities. The mathematical expression representing Bayes' theorem is as follows:

$$P(A \mid B) = \frac{P(B|A) * P(A)}{P(B)} \tag{3.11}$$

P(A|B) is the posterior probability of event A given event B.

P(B|A) is the conditional probability of event B given event A.

P(A) is the prior probability of event A.

P(B) is the prior probability of event B.

Within the framework of a Bayesian network (equation 3.12), this particular equation is used to compute the probability of events or variables by taking into account previous knowledge and observable data, all the while considering the interdependencies that are represented by the structure of the network.

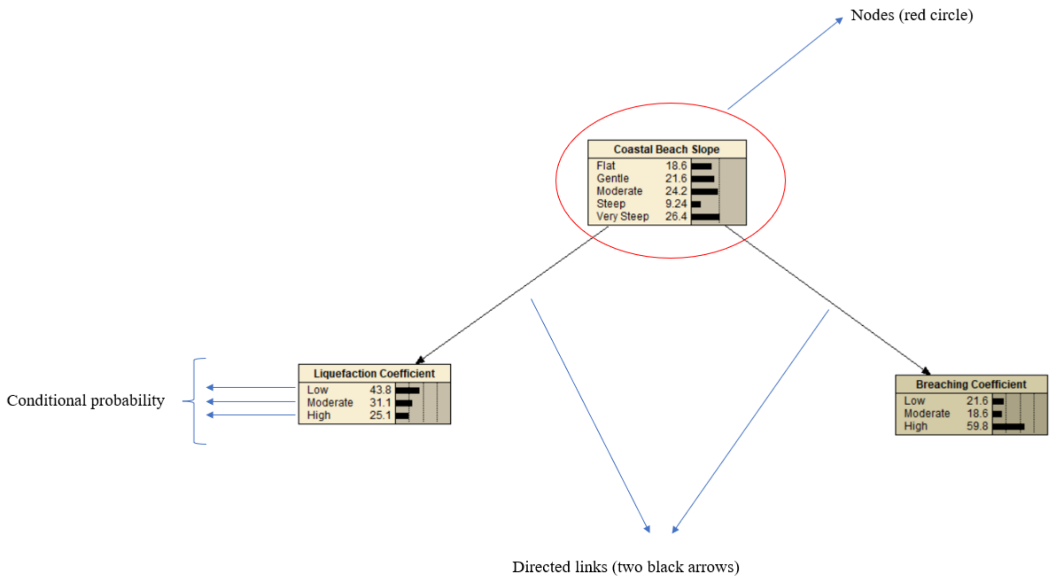


Figure 3.9 : Simple Bayesian network visualization (the whole system is DAG).

This study investigates the probabilistic relationships between various environmental factors and the occurrence of coastal flow slides using a Bayesian network approach implemented in Netica software. By analyzing these relationships, we aim to provide a framework for predicting the likelihood of flow slides under different environmental conditions.

Node definition:

The constructed network comprises eight nodes:

1. Target Node: "Coastal Flow Slide Occurrence", with binary states "Yes" and "No". If yes, either very low, low, moderate, high or very high level.
2. Variable Nodes: Ten nodes representing most influential factors in CFS:
    - Tidal range (m)
    - Slope (degrees)
    - Mean particle size (mm)
    - Internal friction angle (degrees)
    - Significant wave height (SWH) (m)
    - Solid fraction
    - Hydraulic conductivity (cm/s)
    - Hydraulic gradient level (m)
    - Porosity
    - Groundwater level (m)

Each variable node has states based on relevant physical ranges or categories appropriate for the study area.

Relationship specification:

Directed arcs connect the variable nodes to the target node, reflecting their hypothesized influence on coastal flow slide occurrence. Relationships are defined using two primary methods:

- Conditional probability tables (CPTs): Expert knowledge informs the assignment of probabilities to the "Yes" or "No" state of the target node given specific combinations of parent node states (variables).

- Learning from data: If historical data on flow slide occurrences, environmental factors, and their temporal relationships is available, Netica's learning algorithms can be employed to automatically generate CPTs based on the data.

Prior probabilities:

In the absence of strong prior knowledge about the frequency of flow slides, an initial equal probability will be assigned to both "Yes" and "No" states of the target node. These can be adjusted based on expert input or data analysis.

Inference and analysis:

Netica's probabilistic inference algorithms estimate the posterior probability of the target node ("Coastal Flow Slide Occurrence") under various scenarios. This involves:

- Inputting evidence about specific states of variable nodes (e.g., observed high tidal range).
- Running inference to update the probabilities of the target node based on the evidence and network structure.
- Analyzing the resulting probability distribution to assess the likelihood of flow slides under different environmental conditions.

4. DEVELOPMENT OF HYBRID MODEL

4.1 Case Study

Amity Point is a minuscule seaside settlement situated on North Stradbroke Island in the state of Queensland, Australia (Figure 4.1). The location of the site is positioned on the western portion of the island, with a direct orientation towards Moreton Bay. The municipality is renowned for its picturesque landscapes, tranquil ambiance, and diverse fauna.

One of the primary focal points of Amity Point is in its breathtaking coastal areas. The tranquil and transparent nature of the bay's waters makes it a favored destination for recreational activities like as swimming, fishing, and boating. The beaches provide excellent opportunities for leisurely strolls and appreciating the picturesque scenery.

Amity Point is well known for its diverse fauna, with a particular emphasis on the presence of dolphins and turtles. The region is inhabited by a resident group of untamed dolphins, providing the opportunity to see and engage with them within their own environment. The dolphins often exhibit a propensity for approaching the shoreline, so affording tourists a remarkable occasion to engage in observation and maybe even engage in aquatic interaction with these marine creatures.

Amity Point, like to several coastal regions, is prone to coastal erosion, in addition to its inherent aesthetic appeal and recreational prospects. Coastal erosion pertains to the progressive degradation and depletion of land resulting from the impact of waves, tides, and currents. This process may have substantial effects on both natural ecosystems and human-built infrastructure.

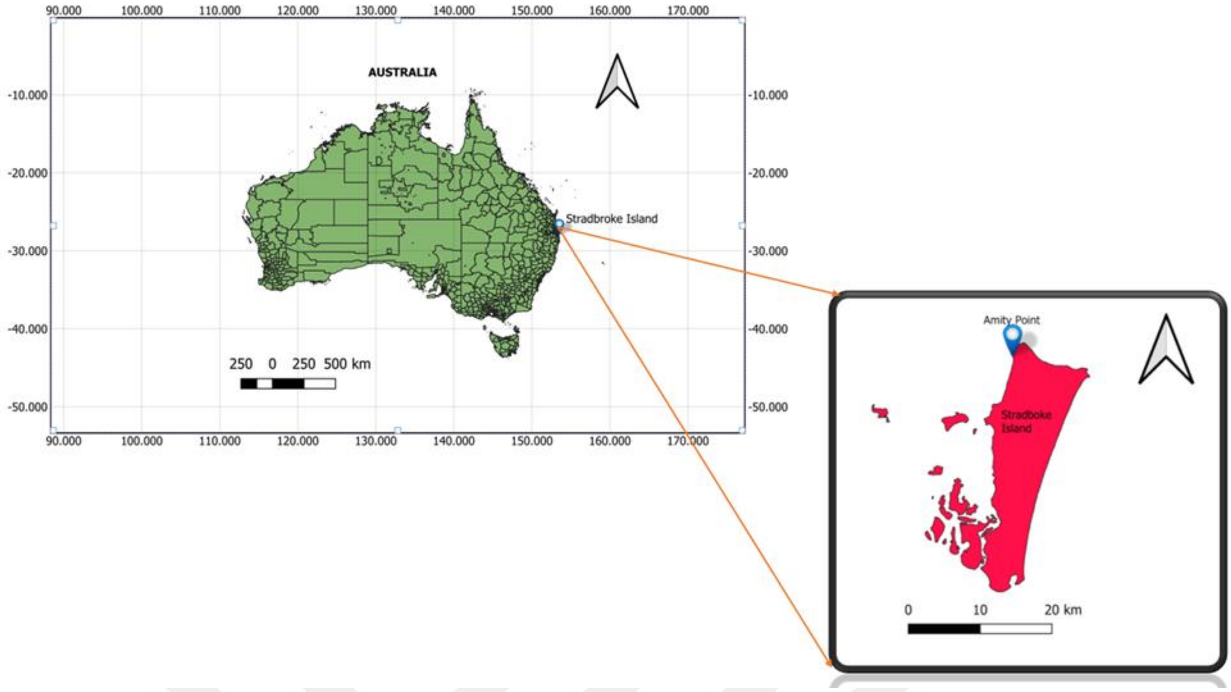


Figure 4.1 : The geographical context of the research site, Amity Point.

Amity Point is well known for its notable occurrences of coastal erosion, as well as its characteristic coastal flow slides. One of the primary issues with the coastline of Central Reach is to the gradual eastward movement of Rainbow Channel, along with the associated risk of flow slides occurring on the submerged slopes of the channel.

In response to the preceding historical hazards, owners of bay-front properties have been consistently implementing the installation of rock armour on susceptible parts. Throughout the duration of the SEMP's (Final Report of the Shoreline Erosion Management Plan) technical research, a conceptualization for a flow slide barrier design was established.

The Redland City Council, in collaboration with relevant stakeholders and expert consultants, conducted a comprehensive assessment of the rock installations situated in the Central Reach and the newly proposed barrier design for coastal protection. This evaluation included geophysical research and a bathymetric survey conducted in Rainbow Channel, aimed at gathering essential data for assessing the effectiveness of existing coastal defenses and proposing improvements where necessary.

The outcomes of this assessment were documented in the Sustainable Energy Management Plan (SEMP), which detailed the evaluation of barrier designs and the findings of the comparative analysis. This documentation serves as a valuable resource for informing future coastal management strategies and decision-making processes in the Redlands area of South East Queensland, Australia..

Figure 4.2 : Amity Point seashore exploration zone.

Flow slides frequently occur in the westernmost region of the Northern Reach, namely at the point where the flow slide barrier originating from the Central Reach ends. The susceptibility of flow slides in this location is mostly attributed to the configuration of the Rainbow Channel and the sand supply patterns seen in the vicinity. It is probable that this vulnerability will endure, and there is a possibility that the frequency of flow slides may escalate as the Rainbow Channel progressively progresses towards the east and reaches the preexisting flow slide barrier of the Central Reach (Figure 4.2).

Given the evolving circumstances, namely in the area where the central reach terminates and the northern reach begins, with the progressive displacement and increased inclination of the sandy slopes along Rainbow Channel, there is an increasing probability of flow slides taking place. The dynamic nature of these changing conditions calls for prompt notice and decisive response.

In order to properly handle this issue, it is imperative to conduct a thorough risk assessment. Conducting such an assessment will facilitate the evaluation of the possible ramifications of coastal flow slides and the development of methods to limit their repercussions. By using this approach, we can guarantee the sustained efficacy of the existing protective barrier.

The comprehensive evaluation of geological and environmental elements that contribute to the hazards associated with flow slides should be included into the risk assessment procedure. Furthermore, it is important to take into account the susceptibility of essential infrastructure and communities located inside the impacted regions. It is essential to engage in collaboration with esteemed professionals specialising in the disciplines of geology, coastal engineering, and environmental science in order to get the necessary data and perspectives for a comprehensive evaluation.

In addition, it is imperative that the risk assessment be not conducted as a singular event, but rather as a continuous endeavour that acknowledges the ever-changing characteristics of coastal ecosystems and the growing array of threats. The consistent monitoring and periodic revision of the evaluation will be essential in order to modify mitigation plans in response to evolving situations.

In conclusion, it is crucial to construct an all-encompassing and regularly updated risk assessment because to the changing circumstances and growing likelihood of coastal flow slides. Implementing a proactive strategy will allow us to ensure the preservation of the protective barrier's integrity and mitigate the potentially catastrophic impacts of flow slides on coastal regions.

In this comprehensive study, we have conducted a thorough evaluation of risks, aiming to develop efficient solutions for mitigating them. The research comprises several essential elements, all of which contribute to a more comprehensive understanding of the dynamics of coastal flow slides and the management of associated risks.

A Bayesian Network has been used to do a risk assessment based on probabilities. This methodology allows for the quantitative evaluation of the probability of coastal flow slides under different circumstances. By integrating probabilistic modelling techniques, it becomes possible to enhance the accuracy of risk estimation and make well-informed judgements pertaining to the implementation of risk mitigation methods.

The application of sensitivity analysis in the context of classification. In conclusion, sensitivity analysis methodologies were devised specifically designed to distinguish between two specific categories of coastal flow slides: Coastal Retrogressive Breaching Flow Slide (CRBF) and Coastal Breaching Liquefaction Flow Slide (LFS).

The categorization of flow slides is of utmost importance as it enables us to customise mitigation techniques according to the unique kind of flow slide, hence enhancing the accuracy of the risk management endeavours.

The research primarily focuses on formulating site-specific solutions. The methodologies and techniques employed, such as 12 years of SWH time series, sensitivity index, Bayesian Network analysis, and enhanced sensitivity analysis, are adaptable and applicable to various coastal areas facing similar challenges. These techniques enhance knowledge and proactive measures in the field of coastal hazard management.

These advanced approaches not only enhance understanding of coastal hazards but also provide valuable insights and proactive measures that can be implemented across different sites to mitigate risks effectively. Therefore, while the research findings may offer specific solutions for the studied site, the methodologies employed hold potential for broader applicability in coastal hazard management.

4.2 Sensitvity Index

To properly detect the danger of Coastal Flow Slide (CFS) failure and designate the most susceptible coastal locations at risk of suffering such failure, we developed the Durap Sensitivity Index (DSI). We devised a complex hybrid model to accomplish this goal, one that ac-counts for all the potential outcomes of flow slides while also accounting for the un-predictability of the variables utilized in the new sensitivity index of DSI.

The invention of the Durap Sensitivity Index (DSI) signifies a notable advancement in the discipline of coastal hazard evaluation. This methodology involves the development of a sophisticated hybrid model that accounts for the intricate characteristics of flow slide dynamics, while also addressing the inherent unpredictability associated with the several factors included into the proposed sensitivity index of DSI.

To effectively assess the risk of coastal flow slides, a comprehensive approach was undertaken, involving various key steps:

- The soil and sediment samples were systematically gathered from the coastal region, with careful consideration given to obtaining a comprehensive representation of various geological layers. Subsequently, all of these materials were rigorously analysed with special consideration given to the elimination of contaminants and the attainment of an optimal condition suitable for further testing (Section 3.1.1).
- Tilting box tests were done in laboratory settings to simulate the circumstances that have the potential to induce coastal flow slides. Prepared soil or sediment samples were placed into an inclined container, which was then tilted to simulate the impact of gravity, moisture, and other pertinent elements. This enabled research to precisely observe the behaviour of the soil while it underwent tilting, so gaining valuable insights on its stability and vulnerability to slide (section 3.1.5)
- As such, it was essential to comprehend the frictional characteristics of the soil found along the shore. The angle at which soil particles commence sliding against each other was determined via the conductivity of friction analysis experiments by research. The angle referred to as the angle of internal friction has been of significant importance in evaluating the likelihood of instability and sliding down the coastal slope (section 3.1.5).
- The evaluation of hazards is heavily influenced by the permeability of the soil or sediment. Hydraulic conductivity tests were conducted in order to assess the permeability of the soil, namely the degree of ease with which water could pass through it. The high hydraulic conductivity implies a quick entry of water, which may elevate the likelihood of saturation and flow slides in the event of intense precipitation or storms (section 3.1.4)
- Although laboratory trials yielded vital data, doing on-site inspections of the coastal region had similar significance. The topography, vegetation, existing infrastructure, and indications of prior erosion or instability were subjected to comprehensive investigations by the researchers. The practical evaluation conducted facilitated the identification of probable factors that might initiate flow slides, including inadequately drained regions, certain slope attributes, and the existence of anthropogenic constructions (Amity Point site inspection).

By considering a wide range of potential consequences linked to flow slides, the DSI was developed. The DSI significantly enhances the ability of pinpointing coastal areas most at risk. It effectively combines advanced scientific knowledge with modern modelling methods to provide a complete and flexible instrument for evaluating coastal hazards. Furthermore, it provides a method to assess the susceptibility of these regions to the variables that contribute to (CFS), thus enabling more knowledgeable decision-making in the field of coastal risk management.

DSI is an innovative tool developed to detect the risk of Coastal Flow Slide (CFS) failure and pinpoint the most vulnerable coastal locations. The DSI utilizes a complex hybrid model that integrates three independent models to achieve high accuracy in predicting the likelihood of CFS failure. The primary gol of this study is to provide a computationally efficient and reliable method for calculating the critical zone of CFS using this novel hybrid model and risk index. Predicting, preventing, and mitigating the negative consequences of CFS failure on coastal regions is projected to be much enhanced by the DSI and by integrating the hybrid model. Calculation of the DSI is determined by using the parameters listed in Table 4.1, where DSI is the coastal flow slides sensitivity index of Durap. This index is calculated by using the following parameters of k_{BF} and k_L, where k_{BF} is the coefficient of breaching and k_L is the liquefaction coefficient.

Table 4.1 : DSI parameters for CFS risk assessment

Qualitative Term	Shoreline erosion/accretion rate (m/month) (P1)	Tidal range (m) (P2)	Slope (P3) (m/m)	Mean particle size (mm) (P4)	Internal Friction angle (ϕ: angle)(P5)	SWH (m) (P6)	Solid fraction (P7)
Very low	<-2	<0.2	Flat: < 5 degrees	0.54 < D50 > 1.70 mm	<10	<0.55	$\Phi min=\frac{\pi\sqrt{3}}{16} \approx 0.3401$
Low	-1.0 to -2.0	0.2-0.4	Gentle: 5–10 degrees	0.28< D50 < 0.54 mm	10- 19	$0.55 - 0.85$	Φmin <Φ< Φcrit
Moderate	-1.0 to +1.0	0.4-0.6	Moderate: 10–20 degrees	0.15<D50 < 0.28 mm	19-23	$0.85 - 1.05$	Φcrit=π/(3√3) ≈0.60
High	1 to 2.0	0.6-0.8	Steep: > 20-30 degrees	D50 < 0.15	23-28	$1.05 - 1.25$	Φcrit <Φ< Φmax
Very high	>2.0	0.8	Very steep: > 30 degrees	D50 < 0.1	>36	>1.25	$\Phi_{max} = \frac{\pi}{3\sqrt{2}} \approx 0.74$

*: very low:1 (lowest) to very high:5 (highest).

The breaching coefficient, symbolised as k_{BF}, is a combination of several important factors, including the pace at which dredging occurs, the features of the slope, the kind of packing material in the geological formation, and the unique driving forces that impact the coastal region being studied.

The calculation of CFS coefficients is given in Equation (4.1).

$$k_i = \sqrt[n]{p_1 x p_2 \ldots \ldots \ldots . . x p_n} \quad (4.1)$$

Equation (4.2) is used as the fundamental basis for the computation of the DSI in areas that are susceptible to either breaching or liquefaction.

Each of the variables represents a different facet of the sediment transport process, and they are labeled as P1 through P7. For example, the Shoreline erosion/accretion rate, denoted by P1, is the quantity of sediment being either eroded or accreated in a certain region.

A collection of constant variables relevant to both the liquefaction and breaching processes is represented by the letter i in Equation (4.1). The qualities of the silt being carried, the durability of the coastal constructions, and similar elements may all be considered further constants.

Predicting the likelihood of liquefaction and breaching in coastal locations requires an understanding and quantification of these factors. Researchers may create models to better forecast and manage the possible harm caused by coastal sand flow by analyzing the many components that contribute to these hazards.

Equation (8) is used to generate the DSI for either breaching-prone or liquefaction-sensitive zones. If the packing type is densely packed and the driving force is mass flow, then these two parameters encompass in the calculation of k_L, since they are the main reasons for the liquefaction type of failure of the slope, as given in Equation (4.2).

$$k_L = \sqrt[6]{p_1 \times p_2 \times p_3 \times p_4 \times p_5 x\, p_6 x p_7} \quad (4.2)$$

DSI is a numerical ranking system used to assess the sensitivity of breaching failure and liquefaction flow slides. It ranges from 1 (very low sensitivity) to 5 (very high sensitivity). The DSI parameters are based on several factors, such as dredging rate, number of coastal structures, slope angle, and packing type (for both loosely and densely packed sediment). Other parameters such as driving force (specifically turbidity current) and mass flow are also considered. Each DSI parameter has a qualitative term and corresponding quantitative range that helps determine the DSI ranking.

Table 4.2 provides a summary of the different slope categories (Flat, Gentle, Moderate, Steep, and Very Steep) based on their angle range and the corresponding description. It highlights the suitability of each slope category for different types of coastal structures based on their required stability and control of Coastal Flow Slides (CFS). Table 4.2 also provides recommendations on the required level of CFS control and additional stabilization measures for each slope category.

Table 4.2 : Slope classification and recommendation for CFS**.**

Slope (P3)	Angle Range	Description
Flat	<5 degrees	Little to no incline, suitable for structures requiring stability and low LFS control
Gentle	5–10 degrees	Gradual incline, suitable for structures requiring moderate LFS control
Moderate	10–20 degrees	Moderate incline, requiring both LFS and CRBF control
Steep	>20 degrees	Steep incline, requiring high CRBF control and slope stabilization (It is not recommended to construct coastal structures)
Very steep	>30 degrees	Extremely steep incline often requires additional stabilization measures such as vegetation to prevent CRBF (It is not recommended to construct coastal structures)

Equations (4.1) and (4.2) are used to generate the DSI for either breaching-prone or liquefaction-sensitive zones. Following that, the main risk levels are described by using the following percentages ranging from Level I: (0–25)%, Level II: (25–50)%, Level III: (50–75)%, Level IV: (75–100)%, respectively. To put it another way, a sensitivity score of Level I indicates the least amount of risk, while a sensitivity score of Level IV indicates the greatest amount of risk. Finally, the Durap Sensitivity Index (DSI) can be written in terms of coastal flow slides and liquefaction flow slides as given in Equation (4.3):

$$DSI = k_L \cdot P(V_{\text{liquefaction}}) + k_{BF} \cdot P(V_{\text{breach}}) \quad (4.3)$$

If the first part of the DSI equation, $k_L \cdot P(V_{\text{liquefaction}})$, is greater than the second part, then the flow slide is dominated by breaching or vice versa, as given in Equations (4.4) and (4.5).

$$1 \leq \frac{k_{BF} \cdot P(V_{\text{breach}})}{k_L \cdot P(V_{\text{liquefaction}})} < 5 \text{ breachingwave height dominated failure} \quad (4.4)$$

$$0 \leq \frac{k_L \cdot P(V_{\text{liquefaction}})}{k_{BF} \cdot P(V_{\text{breach}})} \leq 1 \text{ liquefaction dominated failure} \quad (4.5)$$

kL and kBF serve as a risk classification metric in coastal flow slides vulnerabilities, quantifying the event either is CRBF-dominated liquefaction-dominated. When it comes to DSI, its computation relies heavily on the accurate estimation of these events' probabilities, which is where Bayesian Networks (BN) come into play. BNs are employed within the DSI framework to model the complex and interdependent factors influencing coastal flow slides and liquefaction, such as groundwater level, sea level rise, coastal geology, and tidal dynamics.

The evaluation of liquefaction and breaching probabilities plays a pivotal role in understanding and mitigating the risks associated with coastal flow slides. These phenomena, driven by complex and interdependent environmental factors, pose significant threats to coastal infrastructure and ecosystems. This thesis delves into the application of Bayesian Networks (BNs) in quantifying the probabilities of liquefaction $P(V_{\text{liquefaction}})$ and breaching $P(V_{\text{breach}})$, offering a nuanced approach to risk classification in coastal flow slide vulnerabilities.

The probabilities of liquefaction $P(V_{\text{liquefaction}})$ and breaching $P(V_{\text{breach}})$ are determined from the Bayesian Network. These probabilities are determined using a Bayesian Network, which is a statistical model that can handle complex, uncertain systems by representing variables and their conditional dependencies. For example, groundwater level is affected by sea level rise, precipitation, evapotranspiration, coastal geology, tidal dynamics, aquifer pumping. Sea level rise increases pressure on coastal aquifers, potentially leading to saltwater intrusion. Increased precipitation can raise groundwater levels, while drought leads to a decline. The coastal geology determines how readily groundwater is recharged and how easily it flows. Tidal fluctuations can cause short-term changes in groundwater levels near the coast. Excessive aquifer pumping can deplete groundwater levels and worsen saltwater intrusion.

The justification for employing a Bayesian network in this research is elucidated by the subsequent points:

i. Complex interdependencies: Coastal systems are complex, with many interrelated factors that can influence the occurrence of events like liquefaction and breaching. A Bayesian network can model these interdependencies and provide a structured way to incorporate and analyze them.
ii. Incorporation of uncertainty: Coastal data often come with a degree of uncertainty due to natural variability and limitations in measurement. Bayesian networks are well-suited to handle uncertainty, as they allow for the incorporation of probability distributions for each variable.
iii. Updating with new information: Bayesian networks can be updated with new data as it becomes available. This feature is particularly useful in coastal engineering, where ongoing data collection can refine the understanding of the system and improve the accuracy of probability estimates.
iv. Predictive capabilities: By using a Bayesian network, it eanble to make predictions about the likelihood of liquefaction and breaching based on the current state of CFS and the relationships between variables. This predictive capability is valuable for risk assessment and decision-making.
v. Dealing with incomplete data: Coastal data can sometimes be incomplete or scarce, especially in the preliminary stages of a project. Bayesian networks can be used to make the best use of available data and can be particularly helpful when traditional empirical methods are not applicable due to data limitations.

The application of a Bayesian network in this study allows for a systematic and probabilistic approach to assess the risks of liquefaction and breaching. It provides a means to quantify the likelihood of these events in a manner that accounts for the complex interactions between various factors and the inherent uncertainties present in geotechnical data.

- very low: the parameter has little to no effect on the DSI (Level I);
- low: the parameter has a small effect on the DSI (Level II);
- moderate: the parameter has a moderate effect on the DSI (Level III);
- high: the parameter has a significant effect on the DSI (Level IV);
- very high: The parameter has a very significant effect on the DSI (Level V).

Table 4.3 : Qualitive terms for assessment of coastal flow slides managment strategies.

Qualitative Term	Sea level rise (m) (P8)	Hydraulic gradient (m)	Number of coastal structures (-) (P10)	Beach Width (m)	Historical storm events
Very low	< 1.8	Very Gradual	No	>150	Infrequent, mild storms
Low	1.8 − 2.5	Gradual	1	100-150	Sporadic, mild storm occurrences
Moderate	2.5 − 3.0	Moderate	2	75-100	Coastal regions with regular but typically manageable storm activity
High	3.0 − 3.4	Steep	3	50-75	Coastal areas prone to frequent storms
Very high	> 3.4	Very Steep	>4	<50	Coastal regions with a long history of severe, frequent storms

Table 4.4 : Categorization of historical storm events by severity parameters into qualitative vulnerability categories.

Parameter	Very Low	Low	Moderate	High	Very High
Wind Speed (mph)	< 50	50-74	75-99	100-124	≥ 125
Storm Surge (feet)	< 3	3-6	7-9	10-12	≥ 13
Property Damage ($)	< $1 million	$1-5 million	$5-10 million	$10-50 million	≥ $50 million
Casualties	0	1-10	11-50	51-100	> 100

- Statistical analysis of variables in Table 4.1 and

, including calculations of mean, median, and mode (as depicted in Figure 4.3), informed the development of tailored management strategies for CFS.

a) Sort the variables in ascending order based on their numerical values,

b) Identify the mode as the value with the highest frequency within the ordered dataset,

c) Calculate the median. If the dataset has an even number of values, determine the mean of the two middle values,

d) Calculate the mean of the selected coastal variable.

Upon performing the necessary computations or deriving those elements from the sample, it is possible to state with confidence that the resultant data has undergone comprehensive analysis. Consequently, a thorough distribution figure generated to visually depict the features of the dataset (Figure 4.3). The distribution figure functions as a graphical depiction of the dispersion or allocation of data over different values, providing significant insights into the primary trends and patterns contained within the dataset.

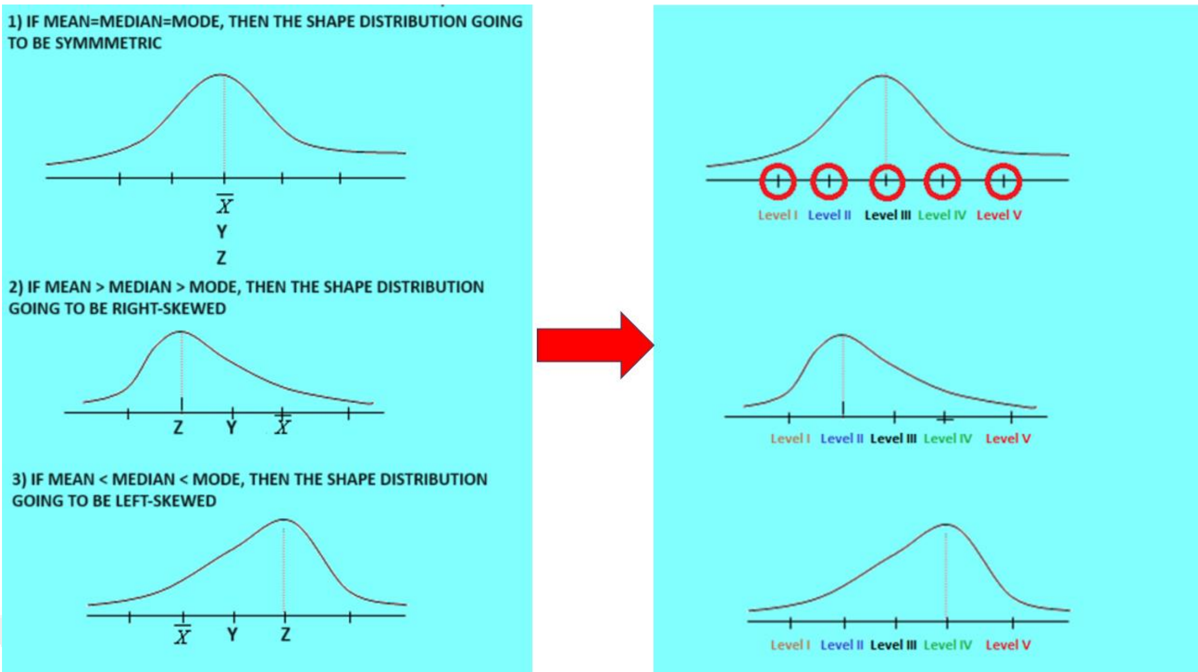


Figure 4.3 : Probability distribution of CFS occurrences based on statistical analysis

The statistical method on the left is used to evaluate the data, and the one on the right is the result achieved in terms of the degree of coastal hazard level could be interpreted as a description of a graph that shows the results of a statistical analysis of CFS data.

The one on the right, is like the answer we get after using that tool. It tells us how safe or risky the coast is. Think of it as a scale that goes from 'very safe' to 'very dangerous.' So, the method on the left helps us figure out where the coast falls on this scale.

4.3 Bayesian Network

The development of a hybrid model for predicting coastal flow slides at Amity Point necessitates a comprehensive approach that combines deterministic and probabilistic methods to account for the complex interplay of environmental factors. A significant component of this hybrid model is the integration of a Bayesian network, also known as a Bayesian belief network or a probabilistic graphical model. This network serves as a visual and mathematical framework to delineate the probabilistic relationships among a myriad of variables influencing coastal flow slide occurrences.

The Bayesian network is constituted by a series of interconnected nodes and directed linkages (edges), where each node represents a random variable, and each edge delineates the probabilistic dependencies between these variables. This network is organized in the form of a Directed Acyclic Graph (DAG), ensuring the absence of cycles and facilitating efficient probabilistic inference. The nodes in this network cover both the target variable—"Coastal Flow Slide Occurrence"—with binary states (Yes/No) and variable nodes representing critical environmental factors such as tidal range, slope, mean particle size, and others.

The construction and analysis of the Bayesian network are executed using Netica software, focusing on elucidating the probabilistic relationships between environmental factors and the likelihood of flow slide events. This involves defining nodes, specifying relationships through directed arcs, and employing conditional probability tables (CPTs) or learning from historical data to estimate the influence of each factor on flow slide occurrences.

At the core of the Bayesian network model lies Bayes' theorem, which facilitates the computation of posterior probabilities by incorporating prior knowledge and observable data. This theorem is instrumental in updating our understanding of the likelihood of coastal flow slides in response to changing environmental conditions.

Through the application of Netica's probabilistic inference algorithms, which has been used by many researchers e.g., (Gutierrez et al., 2011; Jäger et al., 2018; M. Sanuy et al., 2020) (Figure 4.4), the model assesses the posterior probability of coastal flow slide occurrences under various scenarios. This process entails inputting evidence about specific environmental conditions and analyzing how these influence the probability distribution of flow slide occurrences.

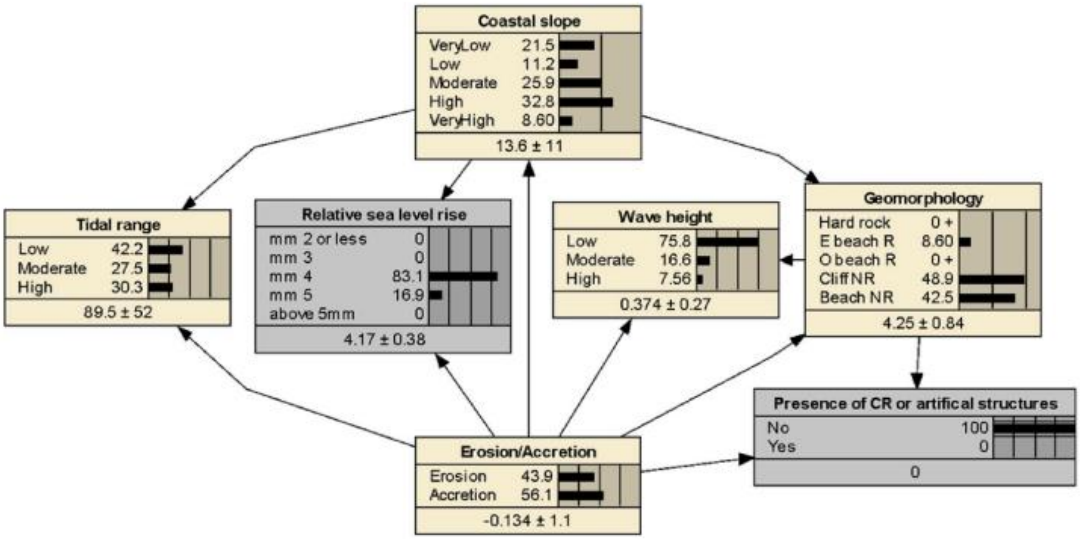


Figure 4.4: BN model for predicting the probability of shoreline change rate (Sahin et al., 2019).

5. RESULTS

5.1 Overview

This chapter presents findings derived from a multi-pronged methodological framework designed to elucidate the complex dynamics of CFS at the Amity Point case study site. Results stem from the rigorous integration of field-based investigations and controlled experimental procedures, culminating in the development of a Bayesian Network (BN) and DSI for enhanced analysis and interpretation in management strategies tailored for CFS.

5.2 The Findings of the Experimental Study and Site Inspection

This research endeavors to elucidate the geomechanical and hydraulic properties precipitating flow slide phenomena, with a keen focus on parameters such as hydraulic conductivity, angle of repose, porosity, retreating velocity, compaction, grain size, and viscosity. Through a series of methodically designed experiments, we aim to unravel the intricate relationships between these variables, particularly the nexus between hydraulic conductivity and compaction. This investigation will facilitate the development of a BN to predict the interplay between CFS and CFS-related parameters. While the influence of the friction angle on flow slide events is recognized, it is considered peripheral to the research's core focus.

This extensive empirical data serves as the bedrock for BN modeling, enhancing the predictive capabilities of this hybrid model regarding CFS dynamics.

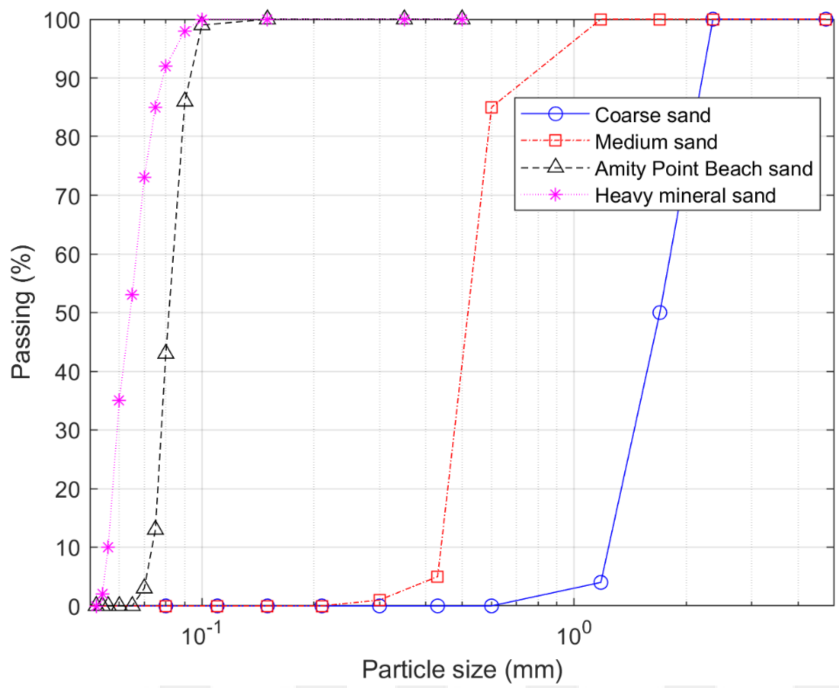


Figure 5.1 : Grain size distribution of APBS, heavy mineral, medium, and coarse sand.

Figure 5.1 shows the particle size distribution curves of four sand types: coarse sand, medium sand, APBS, and heavy mineral sand. The x-axis represents particle size (millimeters) on a logarithmic scale, and the y-axis represents the cumulative percentage of particles passing through sieves of decreasing size.

- The graph is a typical grain size distribution curve, which is commonly used in soil mechanics and sedimentology to categorize particle sizes.
- Coarse sand has the broadest size distribution, with particles ranging widely in size.
- Medium sand shows a more concentrated distribution around a particular particle size.
- Amity Point Beach sand has a distribution that indicates a more uniform particle size, with most particles being very fine.
- Heavy mineral sand shows a very steep curve, suggesting a very narrow particle size range, with almost all particles being of a similar size.

This analysis is based on standard interpretations of grain size distribution curves in geological, civil engineering contexts, and coastal studies, including considerations for coastal flow slides associated with sands like Amity Point sand.

Coastal flow slides have been known to occur in areas with Amity Point sand, and the grain size distribution can influence the occurrence and behavior of these slides. Understanding how granular materials interact with fluids is crucial in assessing such phenomena.

These insights serve as a foundation for the subsequent exploration of experimental findings. This section delves into a series of controlled experiments aimed at elucidating the intricate interplay between various physical parameters and fluid dynamics within porous materials.

Eight experiments were conducted, each designed to probe the nuances of fluid flow through porous media. Two distinct fluid types were employed: water and silicone oil. The choice of silicone oil stems from its differing viscosity compared to water. This allows for this research to examine how fluid viscosity influences flow behavior.

Key variables investigated in these experiments included grain density, porosity range, median particle diameter (d50), coefficient of uniformity (d90/d10), fluid viscosity, and retreating velocity. Retreating velocity refers to the speed at which a fluid withdraws from a porous medium (such as when liquid drains from a sponge).

To offer clarity and facilitate understanding, it was tabulated the experimental details and outcomes in a structured manner (Table 5.1).

Water Experiments (Experiments 1-4):

Grain density exhibited variations, with higher density observed in Experiments 1 and 5, and lower density in Experiments 3 and 7.

Porosity remained relatively stable in water experiments, with notable exception in Experiments 3.

Median particle diameter (d_{50}) evolved incrementally from 0.15mm to 1.70mm, accompanied by corresponding shifts in the coefficient of uniformity.

Fluid viscosity was constant at 1.0 x $10^{\wedge -3}$ Pas.

Silicone Oil Experiments (Experiments 5-8):

Grain density displayed variation, with heightened density in Experiment 5 and reduced density in Experiment 7.

Porosity levels mirrored those in the water experiments, showing consistency.

Median particle diameter (d_{50}) exhibited a parallel trend to the water experiments.

Fluid viscosity for silicone oil was notably higher, accentuating its distinct characteristics from water.

From these experiments, several noteworthy conclusions emerge:

Retreating velocity tended to be significantly lower in silicone oil due to its heightened viscosity relative to water.

A consistent trend of decreasing retreating velocity was observed with increasing grain density, suggesting a pronounced influence of grain density on fluid flow resistance.

Variations in porosity and grain size across the experiments underscore their pivotal role in shaping retreating velocity within porous materials.

Table 5.1 : Volume fraction of granular materials in water and silicone oil.

Experiment No.	Fluid	Fluid Viscosity (Pa*s)	Grain density (t/m^3)	Porosity range	d50 (mm)	$\frac{d90}{d10}$	Retreating Velocity (cm/s)
1	Water	10^{-3}	4.41	0.35-0.46	0.15	1.92	0.51
2			2.65	0.37-0.44	0.28	1.91	0.76
3			2.01	0.26	0.54	1.74	6.68
4			2.83	0.36	1.70	1.75	9.24
5			4.41	0.37-0.44	0.15	1.92	0
6	Silicone oil	$4x10^{-3}$	2.65	0.35-0.46	0.28	1.91	0
7			2.01	0.26	0.54	1.75	2.58
8			2.83	0.36	1.70	1.75	3.09

The insights gained from these experiments bear substantial significance for the assessment of risks associated with coastal flow slides.

The observed relationship between grain density and retreating velocity suggests that regions with finer grain of sand such as Amity Point, be at a heightened risk of coastal flow slides. This knowledge allows for more targeted risk assessment in areas with similar geological characteristics.

Understanding the influence of porosity and grain size on fluid flow behavior aids in identifying vulnerable zones along coastlines. Areas with reduced porosity or specific grain size distributions may be prone to increased susceptibility to flow slides, warranting closer monitoring and preventive measures.

By considering fluid properties and their impact on retreating velocity, risk assessments can incorporate factors such as fluid viscosity, providing a more comprehensive understanding of potential coastal flow slides dynamics. In addition to fluid viscosity, it is crucial to account for other factors like the hydraulic conductivity of different sand types, including Amity Point beach sand.

Figure 5.2 provides a visual representation of the outcomes derived from this experimental study, specifically illustrating the relationship between hydraulic conductivity and solid fraction test results. This graphical depiction serves as a clear and informative summary of the findings obtained through this rigorous investigation

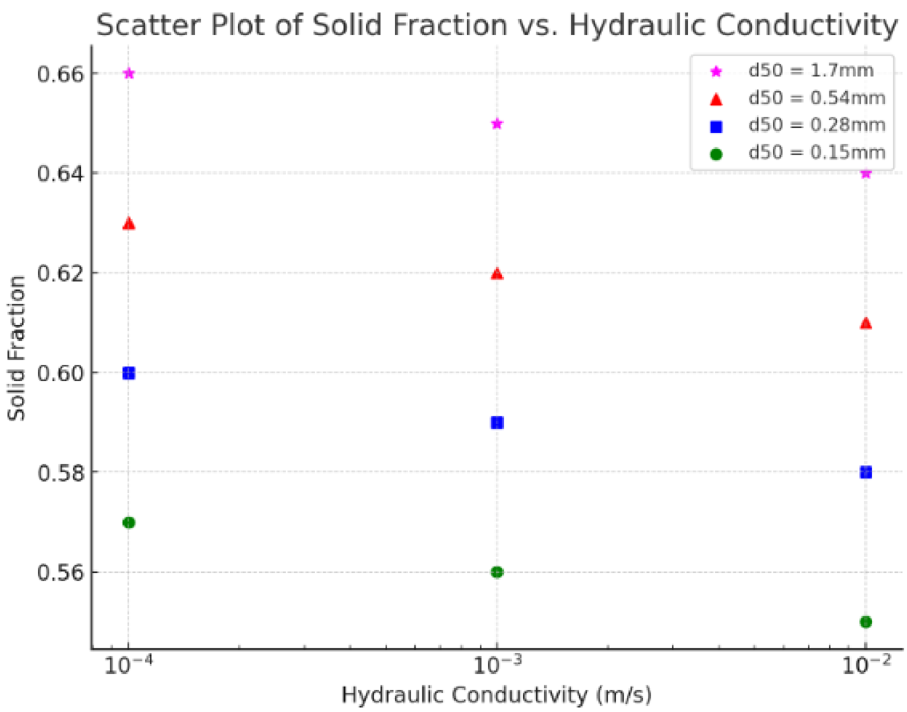


Figure 5.2: Solid fraction vs hydraulic conductivity for APBS, heavy mineral, medium, and coarse sand

Figure 5.2 shows a negative correlation between solid fraction and hydraulic conductivity. This means that as the solid fraction increases, the hydraulic conductivity decreases. This is because there is less space for water to flow through the sediment when the solid fraction is higher.

Solid fraction: In the context of coastal flow slides, solid fraction likely refers to the amount of sediment in the soil. A higher solid fraction means there is less space for water to occupy, and the sediment particles are packed closer together. This can have several implications for this particular study:

- Reduced pore space: With less pore space, there is less room for water to flow through the sediment, which can decrease the hydraulic conductivity.
- Increased friction: As sediment particles are packed closer together, there is more friction between them, which can also hinder water flow.
- Greater resistance to deformation: A higher solid fraction can make the sediment more resistant to deformation, which can help to prevent slope failure. However, if the pore pressure increases significantly, it can overcome this resistance and trigger a slide.

Hydraulic conductivity: A higher hydraulic conductivity indicates that water can flow more easily through the sediment. This can have several implications:

- Rapid pore pressure changes: If the hydraulic conductivity is high, pore pressure changes can occur quickly, which can destabilize the slope and contribute to coastal flow slides.
- Tide fluctuations: When the tide level drops, water needs to drain from the landward side of the slope to the seaward side. If the hydraulic conductivity is high, this drainage can occur more quickly, reducing the risk of pore pressure buildup and coastal flow slides.

Coastal flow slides: Coastal flow slides can occur when a combination of these factors leads to the buildup of pore pressure in the sediment, exceeding the shear strength of the soil alongside high hydraulic gradient level and triggering a failure. The results suggest that:

Thus, the study sheds light on how solid fraction, influenced by particle size and moisture content, can be a key parameter in assessing the risk of coastal flow slides (Figure 5.3).

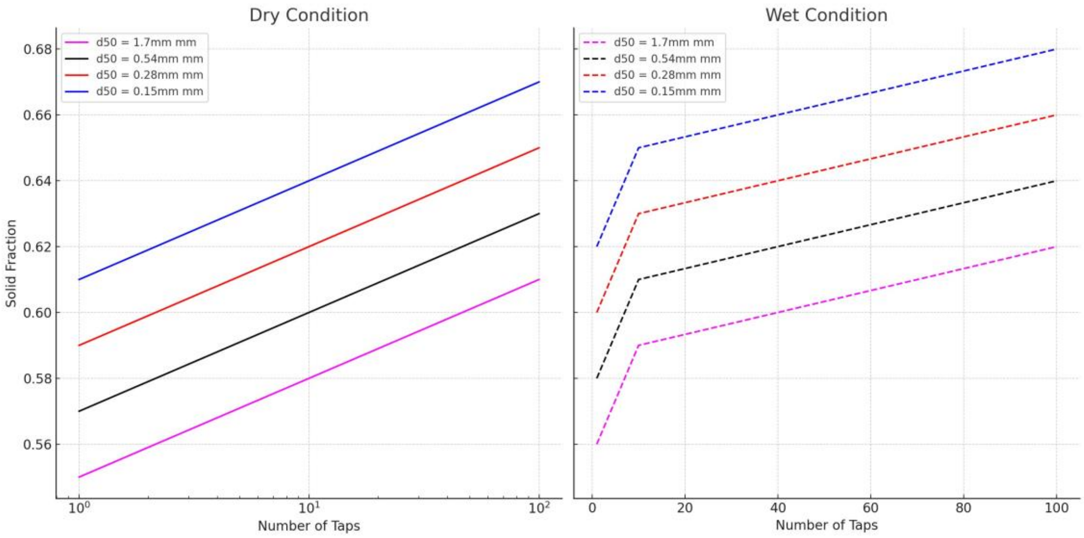


Figure 5.3 : Comparison of hydraulic conductivity of APBS, heavy mineral, medium, and coarse sand

The tilting experiment was designed to understand the compaction behavior of granular materials under repetitive tapping, which can be a proxy for the cyclic loading that might occur in coastal environments. Figure 5.3 shows that solid fraction evolves in response to increasing tap count as measured in tilting box experiments. Data represents (dry/saturated=wet) sand of APBS, heavy mineral, medium, and coarse sand. The x-axis is a logarithmic scale representing the number of taps applied to 4 different sand type. The y-axis measures the solid fraction, which indicates the packing density of the material. There are four sets of data points, each corresponding to a different median particle size (d50), a measure of the grain size.

Smaller particles exhibit a greater increase in solid fraction with tapping. This is due to the smaller particles' ability to fill voids between larger particles more efficiently, leading to a more compact structure.

Both conditions show compaction with tapping, but the wet condition demonstrates a higher initial solid fraction. The rate of increase in solid fraction with tapping appears to be more pronounced in dry conditions, suggesting that water may inhibit compaction over time.

The experimental results suggest that both dry and wet granular materials can compact under cyclic loading, but the mechanisms differs due to the presence of water.

Usefulness for coastal flow slides risk assessment:

Building upon the significance of solid fractions, both under dry and saturated conditions, for slope stability, this study focuses subsequent analysis on examining hydraulic conductivity and solid fraction evolution within two distinct Amity Point sand samples. Figure 5.4 provides an exhaustive visualization of CFS at Amity Point.

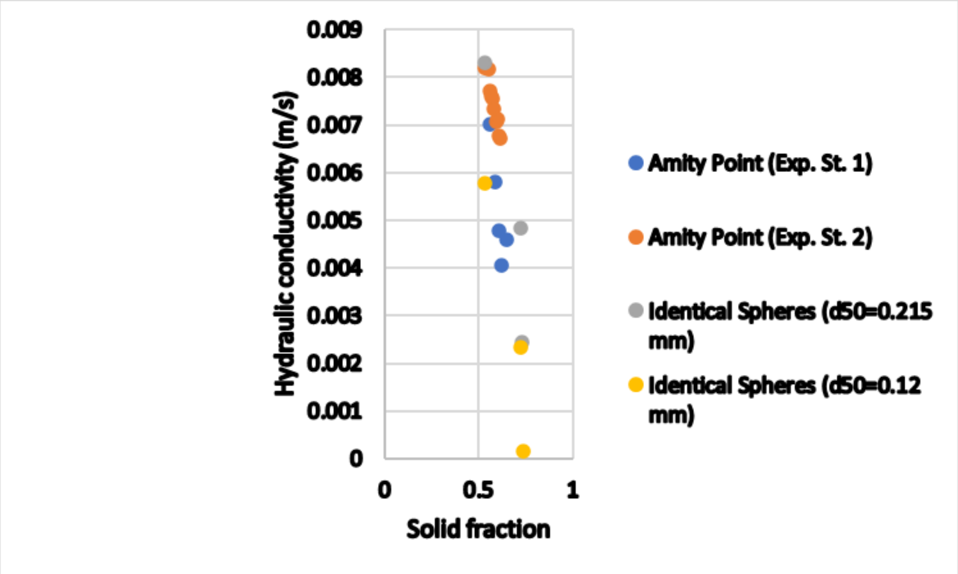


Figure 5.4: Hydraulic conductivity and solid fraction variations in two Amity Point sand samples

Figure 5.4 illustrates the relationship between the solids fraction of a material and its hydraulic conductivity, which is an important factor in geotechnical and hydrogeological studies, including coastal flow slide risk assessment. Here is a detailed explanation of the figure elements:

Hydraulic Conductivity:

Hydraulic conductivity represents a critical parameter in evaluating the potential for coastal flow slides. This property directly influences the velocity of pore fluid migration through sediments. Reduced hydraulic conductivity fosters elevated pore water pressures, potentially culminating in sediment destabilization and an increased propensity for flow slide initiation.

Solids Fraction:

A higher solids fraction typically indicates denser packing of sediment particles, which can reduce the spaces through which water flows, thus reducing hydraulic conductivity. As seen in the equation, an increase in solids fraction results in a decrease in hydraulic conductivity, which can contribute to increased pore water pressure during rapid loading or stress changes.

Internal angle of frcition:

As the name implies, internal angle of friction of a soil or granular material begins to slide upon itself without additional external force. A higher angle of internal friction means the material is more resistant to sliding. However, tapping causes particle rearrangement leading to a denser configuration (compaction). Thus internal angle of friction is influenced by compaction rate alongside factors such as particle shape, size distribution, density, and moisture content.

This study investigated the behavior of soil properties using four distinct sand types in both dry and wet conditions. Figure 5.3 demonstrates that, in dry conditions, increasing the number of taps generally caused an increase in the internal angle of friction, particularly in loose soils. This effect likely plateaued as soils approached their near-maximum density (maximum solid fraction).

Similarly, tapping wet soils increased density and the angle of friction. However, as water content increased towards saturation, the lubricating effect of water decreased interparticle friction and potentially diminished the internal angle of friction. Compared to the other sand types, APBS consistently exhibited a higher internal angle of friction in both wet and dry conditions, suggesting its potential suitability for use in CFS.

In this study, 4 diffrent types of sand were used in both wet and dry condition to facilitate understanding behaviour of soil properties (Table 5.2). In dry condition, the number of taps leads to an increase in the internal angle of friction, especially in loose soil. However, after a point, further tapping did not substantially change the angle of friction as the soil likely reaches a near-maximum density (max solid fraction). While in wet condition, tapping increased density and thus the angle of friction, similar to dry soil. However, as water content increases and the soil approaches saturation, water starts lubricating the particles. This reduces the friction between particles, leading to a potential decrease in the internal angle of friction. As can be seen from Table 5.2, in both and wet condition internal angle of friction for APBS is higher than other thypes of sands used in this study, hence, results showed that APBS is prospenity for CFS as we substantiated this findings with filed measurement.

The table reveals a consistently higher internal angle of friction for APBS in comparison to other sand types under both wet and dry conditions. This can likely be attributed to the unique surface morphology and particle size distribution of APBS. These properties promote greater interlocking and frictional resistance, making APBS a highly valuable material for CFS experimental studies. This provides substantial corroboration for the hypothesis that CFS manifests with greater prevalence in locations characterized by materials possessing a large internal angle of friction.

Table 5.2: Effect of tapping on ınternal angle of friction in different sands

Type of Sand	**Internal angle of friction (ϕ) in dry condition alongside number of taps**			**Internal angle of friction (ϕ) in wet condition alongside number of taps (ϕ)**		
	No tapping	20 taps	80 taps	No tapping	20 taps	80 taps
HMS	28	32	38	31	34	39
APBS	36	56	61	37	38	40
MGS	28	36	38	34	38	39
CGS	23	30	34	24	29	30

5.3 Coastal Flow Slide Risk Assessment: Harnessing Hydraulic Conductivity, Solids Fraction, and Experimental Findings

The experimental studies outlined illuminate several pivotal relationships that directly inform the assessment of coastal flow slide (CFS) risk. Let us break down the crucial findings and their real-world implications:

- Hydraulic Conductivity and Solids Fraction: An Inverse Relationship

The negative correlation between hydraulic conductivity and solids fraction (Figures 5.2 and 5.10) is a core principle in CFS risk analysis. Coastal zones with finer-grained sediments (like Amity Point sand), which tend to have higher solids fractions, will generally exhibit lower hydraulic conductivity. This means water has difficulty draining through the sediment. During events like rapid wave action, tidal changes, or heavy rainfall, pore water pressure can build up within these sediments, reducing their strength and increasing the likelihood of a flow slide.

- The Impact of Grain Size and Porosity

Grain size and the resulting porosity of sediment are major factors influencing CFS risk. Finer-grained sands (typical of Amity Point) generally have lower hydraulic conductivity, making them more vulnerable. Variations in porosity indicate how loosely or densely packed the grains are; densely packed sediments further impede water flow. For risk assessment, this means areas with those characteristics warrant monitoring.

- Cyclic Loading and Sediment Compaction

The tilting box experiments demonstrate that both wet and dry sands compact under repetitive loading, simulating environmental impacts like the constant action of waves, and tides. Importantly, wet conditions appear to initially pack the material tighter, but their compaction potential decreases over time. This suggests that while initially stable, repeated wet conditions may gradually destabilize certain types of coastal slopes.

- Implications for Risk Mitigation and Early Warning

    1. Geotechnical Design: Understanding compaction potential helps inform coastal structure design. Areas prone to wave action might benefit from materials that compact well under dry conditions (like certain larger grain sizes) for embankments or barriers.

    2. Monitoring: Tracking solids fraction of coastal slopes could function as an early warning sign. Areas showing declining solids fraction (potentially through sampling and testing) warrant increased attention, as this may precede a flow slide event.

    3. Drainage: In zones with already high solids fraction but dry conditions, drainage systems may be essential. Diverting water can reduce moisture levels in the sediment, helping maintain stability.

Having established the significance of sand type on solid fraction and hydraulic conductivity, we subsequently delved into the realm of breach dynamics. In particular, we explored the intriguing relationship between breach height and breach velocity, two crucial variables in hydraulic engineering and disaster management. Breach height denotes the vertical elevation at which a breach or rupture occurs within a structure, often a critical factor in dam safety and flood control. In contrast, breach velocity refers to the speed at which water flows through the breach once it has been initiated.

Understanding this dynamic interplay between breach height and breach velocity holds paramount importance in predicting and mitigating potential disasters.

The culmination of this experimental efforts yielded valuable insights, and it presented the findings of this study graphically in Table 5.3 with the help of Table 3.1, illustrating the empirical relationship between breach height and breach velocity.

Table 5.3: Relationship between breach velocity and breach height (Tilting box experiment).

Experiment no	Mean particle size (D50) (mm)	Slope (m/m)	Specific gravity of material (g/cm3)	Elapsed time for fully tilting	Box speed (m/s)	Box face	Breach height (m)	Breach velocity (m/s)
1	0.215	10.7	2.65	1.88	0.128	40	0.0781	0.00416
2	0.215	11.02	2.65	1.78	0.135	40	0.0826	0.00427
3	0.215	11.79	2.65	1.60	0.150	20	0.0931	0.00450
4	0.215	12.14	2.65	1.55	0.155	40	0.0976	0.00458
5	0.215	12.64	2.65	1.65	0.145	20	0.0983	0.00443
6	0.215	12.96	2.65	1.74	0.138	20	0.0983	0.00432
7	0.215	13.42	2.65	1.68	0.143	20	0.1036	0.00440
8	0.215	14.4	2.65	1.93	0.124	40	0.1036	0.00410
9	0.215	15.31	2.65	1.95	0.123	40	0.1096	0.00408
10	0.215	15.68	2.65	1.91	0.126	40	0.1134	0.00412
11	0.215	16.67	2.65	1.95	0.123	20	0.1194	0.00408
12	0.215	17.14	2.65	2.06	0.116	40	0.1194	0.00397
13	0.215	17.22	2.65	1.93	0.124	40	0.1239	0.00410
14	0.215	17.07	2.65	1.75	0.137	40	0.1291	0.00431
15	0.215	16.9	2.65	1.65	0.145	40	0.1314	0.00443
16	0.215	15.53	2.65	1.48	0.162	40	0.1276	0.00468
17	0.215	15.82	2.65	1.39	0.173	40	0.1344	0.00484
18	0.215	15.88	2.65	1.35	0.178	40	0.1366	0.00490
19	0.215	13.97	2.65	1.29	0.186	40	0.1231	0.00502
20	0.215	17.42	2.65	1.37	0.175	40	0.1486	0.00486
21	0.215	18.24	2.65	1.52	0.158	40	0.1479	0.00462
22	0.215	18.57	2.65	1.56	0.154	24	0.1486	0.00456
23	0.215	18.77	2.65	1.61	0.149	24	0.1479	0.00449
24	0.215	19.24	2.65	1.68	0.143	24	0.1486	0.00440
25	0.215	19.11	2.65	1.74	0.138	24	0.1449	0.00432
26	0.215	23.06	2.65	1.83	0.131	24	0.1704	0.00421
27	0.215	20.33	2.65	1.39	0.173	24	0.1727	0.00484
28	0.215	19.73	2.65	1.35	0.178	24	0.1697	0.00490
29	0.215	19.11	2.65	1.31	0.183	24	0.1667	0.00497
30	0.215	19.06	2.65	1.37	0.175	24	0.1629	0.00487
31	0.215	17.7	2.65	1.31	0.183	24	0.1547	0.00498
32	0.215	18.15	2.65	1.16	0.206	40	0.1682	0.00528
33	0.215	19.22	2.65	1.23	0.195	40	0.1734	0.00514

Table 5.3(continued): Relationship between breach velocity and breach height (Tilting box experiment).

34	0.215	20.01	2.65	1.23	0.195	40	0.1802	0.00513
35	0.215	19.37	2.65	1.12	0.215	40	0.1832	0.00539
36	0.215	25.11	2.65	1.33	0.180	40	0.2177	0.00494
37	0.215	39.59	2.65	1.76	0.137	40	0.2988	0.00430
38	0.215	44.05	2.65	1.69	0.142	40	0.3386	0.00438
39	0.215	47.73	2.65	1.98	0.121	40	0.3393	0.00405
40	0.215	48.45	2.65	2.04	0.118	40	0.3393	0.00399
41	0.215	49.94	2.65	2.16	0.111	40	0.3401	0.00388
42	0.215	53.6	2.65	2.00	0.120	40	0.3791	0.00403
43	0.215	57.57	2.65	2.33	0.103	40	0.3769	0.00373
44	0.215	59.67	2.65	2.48	0.097	40	0.3791	0.00362
45	0.215	60.84	2.65	2.58	0.093	40	0.3791	0.00355
46	0.215	62	2.65	2.70	0.089	40	0.3776	0.00347
47	0.215	64.86	2.65	2.93	0.082	40	0.3791	0.00333
48	0.215	71.05	2.65	3.51	0.068	40	0.3791	0.00304
49	0.215	58.05	2.65	2.11	0.114	40	0.3994	0.00392
50	0.215	20.69	4.4	5.61	0.043	24	0.1126	0.00310
51	0.215	20.38	4.4	4.85	0.050	24	0.1239	0.00321
52	0.215	18.59	4.4	4.40	0.055	24	0.1187	0.00337
53	0.215	18.85	4.4	4.20	0.057	24	0.1232	0.00345
54	0.215	21.52	4.4	4.64	0.052	24	0.1337	0.00328
55	0.215	23.95	4.4	4.64	0.052	24	0.1488	0.00328
56	0.215	25.26	4.4	4.82	0.050	24	0.1540	0.00322
57	0.12	24.51	4.4	2.41	0.100	24	0.1578	0.00340
58	0.12	24.93	4.4	2.32	0.104	24	0.1638	0.00347
59	0.12	24.41	4.4	2.20	0.109	24	0.1646	0.00356
60	0.12	27.84	4.4	2.34	0.102	40	0.1819	0.00345
61	0.12	27.52	4.4	2.47	0.097	40	0.1751	0.00336
62	0.12	28.8	4.4	2.59	0.093	40	0.1789	0.00328
63	0.12	29.75	4.4	2.03	0.118	40	0.2091	0.00371
64	0.12	43.19	4.4	2.96	0.081	40	0.2511	0.00307
65	0.12	45.44	4.4	2.32	0.104	40	0.2986	0.00347

Table 5.3 shows that the breach height and breach velocity increase with increasing specific gravity and slope angle. This is because a higher specific gravity means that the material is denser and heavier, and thus more difficult to erode. A steeper slope angle also means that there is more gravitational force acting on the material, which can lead to a higher breach velocity.

It also shows that the tilting box face angle has a complex relationship with breach height and breach velocity. For example, at a specific gravity of 2.65, the breach height and breach velocity first increase and then decrease as the tilting box face angle increases. This is because there is a competition between the gravitational force acting on the material and the frictional force between the material and the tilting box face. At low tilting box face angles, the gravitational force is dominant and leads to higher breach height and breach velocity. However, at high tilting box face angles, the frictional force becomes more dominant and reduces the breach height and breach velocity.

The influence of the box face, combined with box speed, on breach characteristics is notable. A larger box face, especially when paired with higher box speeds, appears to contribute to greater breach heights and velocities.

In addition, an in-depth analysis of the groundwater level was undertaken in order to clarify the complex correlation between coastal flow slides and the variability of groundwater levels in the area. The objective of this study was to gain a deeper understanding of the potential impact of fluctuations in groundwater levels on the occurrence and severity of coastal flow slides. By doing so, this research contributes to the broader comprehension of the intricate interplay between geological factors and environmental conditions in this vulnerable region (Figure 5.5)

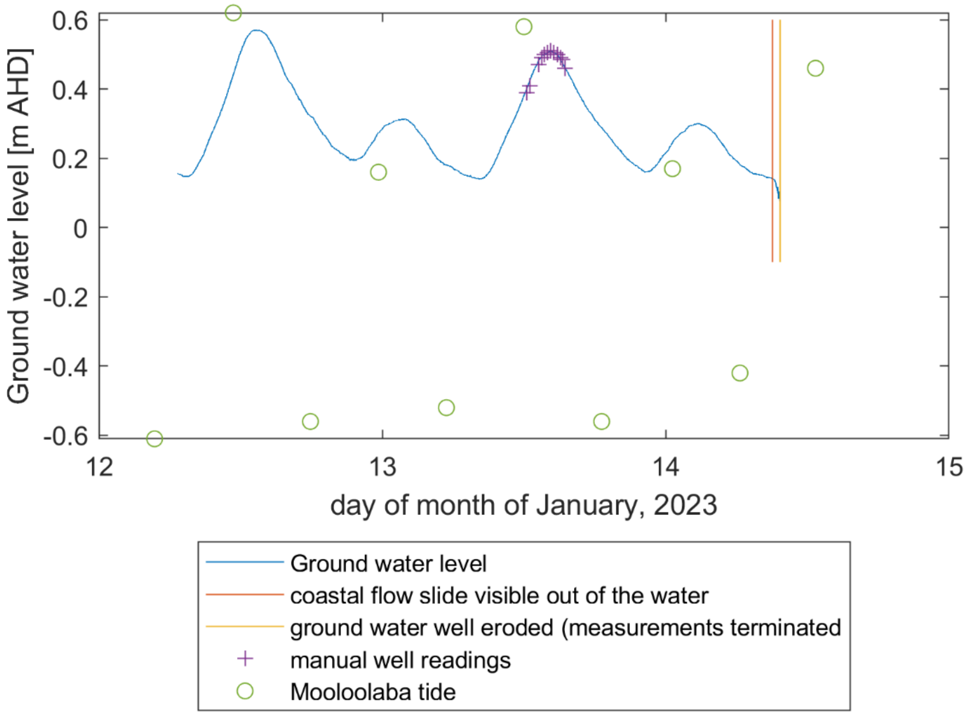


Figure 5.5 : The readings of the groundwater well taken two days before to the occurrence of the coastal flow slide on January 14th.

Figure 5.5 tracks "Ground water level [m AHD]" over a period from the 12th to the 15th of January, 2023. AHD stands for "Australian Height Datum." It is the national vertical datum for Australia, representing the height above mean sea level.

As evident in the figure, coastal flow slides are strongly correlated with localized drops in groundwater level. Notably, the figure demonstrates two distinct points of groundwater level decline. Coastal flow slides initiate specifically at the location of the second groundwater drop. This phenomenon attributed to several factors:

- Sediment accumulation and compaction: The region surrounding the second groundwater drop likely exhibits sufficient sediment accumulation and compaction. This creates a denser, less stable substrate.
- Critical slope stability: The coastal slope in this area reached a critical angle where stability is compromised.
- Internal angle of friction: The internal angle of friction within the sediment likely reaches its maximum value, rendering the material unable to withstand the increased hydraulic gradient forces.

- Hydraulic gradient: The drop in groundwater level creates a steeper hydraulic gradient, exerting greater force on the coastal slope. This increased force exceeds the material's shear strength, ultimately leading to localized slope failure.

- Figure analysis indicates similar patterns on days 13 and 14. However, CFS occurred on January 14th. This is attributed to sediment accumulation, compaction, hydraulic gradient etc. not reaching levels sufficient to impede water flow through the beach sediment gap, a key factor in CFS prevention.

Hydraulic Gradient and Low Tide Levels

Hydraulic gradient refers to the slope created by changes in water levels across different points, which drives the flow of groundwater.

A higher hydraulic gradient is often observed during low tide levels because the difference in elevation between the groundwater and the tidal water level increases.

The groundwater level fluctuations correlate with the tides, the lowering tide created a steeper hydraulic gradient, potentially increasing the velocity of groundwater flow towards the sea.

Destabilization of Coastal Slopes

- Increased groundwater flow can lead to the removal of fine materials from the soil matrix, a process known as internal erosion or "piping," which can weaken the soil structure.

- If the soil or sediment has low cohesion or is loosely packed, the increased hydraulic gradient can cause the soil particles to become dislodged, leading to a decrease in shear strength and potentially triggering a flow slide.

- The steep hydraulic gradient during low tide levels, as indicated by the correlation between groundwater level drops and low tides, could therefore act to destabilize the coastal slope, increasing the risk of a coastal flow slide.

- The event marked by the "coastal flow slide visible out of the water" could be an instance where the lowering tide and the corresponding increase in the hydraulic gradient led to the exposure and potential failure of a portion of the coastal slope.

Conclusions with Risk Assessment Integration

- The data suggests that the risk of coastal flow slides is heightened during low tide due to increased hydraulic gradients, which can destabilize the slope by enhancing soil erosion and reducing soil strength.
- The occurrence of groundwater well erosion on the graph indicates that such destabilizing effects may already be in action, and the integrity of coastal slopes could be compromised.
- Mitigation measures might include reinforcing coastal slopes, improving drainage to reduce hydraulic gradients, and implementing alert systems that consider both tidal data and groundwater level changes to warn of potential slope failures.

This analysis underscores the importance of integrated monitoring systems that take into account the complex interactions between tides, groundwater, and soil stability to manage and mitigate coastal geotechnical hazards effectively.

Coastal flow slides are most likely to occur in areas where the tide level is high and the current speed is fast. This is because the combination of high tide level and fast

There is a correlation between the tide levels and other measurements, indicating that tidal forces affect groundwater levels and coastal conditions (Figure 5.5). The data could be used to understand the impact of tides on coastal groundwater levels and erosion patterns Analysis of these two figures yields the following conclusions:

1. High Tide Level: When the tide is high, the water level near the coast increases. This rise in water level can also elevate the groundwater level in the adjacent land areas. As the groundwater level rises, it saturates the soil, making it heavier and more prone to movement.
2. Fast Current Speed: A fast-moving current exerts bed shear stress on the seabed. This force can be substantial enough to disturb the stability of the sediment or soil that makes up the seabed.
3. Interplay and Resulting Instability: The combination of high tide (and the consequent increased groundwater level) with the drag force from a fast current creates a unique set of conditions. After the tide level decreases, there is often a residual effect on the slope's stability. The soil or sediment, now heavier and

destabilized, is subjected to a hydraulic gradient (the difference in water level between the high tide and the current level). This gradient can create additional stress on the slope.

4. Triggering Coastal Flow Slides:

- High Tidal Range: Areas with substantial differences between high and low tides increase the likelihood of CFS.
- Groundwater Fluctuations and Hydraulic Gradients: High tides raise groundwater levels. When tides recede, groundwater may remain elevated. This creates a hydraulic gradient (pressure difference) between shoreward and seaward areas, exerting force on the beach.
- Sediment Accumulation and Compaction: Sediment buildup along the shore, especially during tide shifts, compacts the soil, restricting water flow.
- Steep Slope: Accumulated sediment creates a steeper coastal slope. Steeper slopes combined with tidal changes increase hydraulic gradients and force pressure differentials, potentially destabilizing the seabed.
- Soil Characteristics: Soil composition is critical. Soils with high angles of internal friction (stronger when dry) can impede water flow. During high tides, this blockage amplifies hydraulic pressure. If that pressure exceeds the soil's strength, a CFS can occur.

This process highlights the importance of understanding the dynamic interactions between tidal movements, current speeds, and the geotechnical properties of coastal slopes for predicting and managing the risks associated with coastal flow slides.

5.4 Discussion of Site İnspection

This study presents the key findings and observations obtained from this comprehensive investigation into sediment accumulations in coastal areas during cyclic tidal level variations. This research has illuminated the intricate processes governing sediment dynamics in these environments. The results are organized as reads and CFS contingent upon a confluence of environmental and geotechnical parameters. The conditions aconducive to CFS are multifaceted and need to be satisfied together, not separately, to trigger CFS events. These conditions include:

Steep slope:

The inclination of the coastal terrain plays a pivotal role in the initiation of CFS. Steep slopes are inherently more susceptible to gravitational forces, which can precipitate the downward movement of sediment and soil.

Tidal fluctuations:

Tidal fluctuations lead to changes in water levels between the landward and seaward sides of a coastal area. When the water level on the seaward side is high enough, it can exert a force that overcomes the internal angle of friction of the sediment. This is particularly relevant in places like Amity Point, which is known for its high internal angle of friction. As a result of these tidal forces, there is an increase in groundwater levels on the landward side, which in turn establishes a hydraulic gradient across this specific coastal region.

Groundwater level variation:

High tide events contribute to an elevation in the groundwater level along coastal areas. This increase is attributed to the influx of seawater during high tide. Through this study, monitoring and data analysis highlighted the pronounced influence of tidal fluctuations on groundwater levels.

Sediment accumulation during tidal cycles:

This study confirmed that sediment accumulations occur during cyclic tidal level variations. It was observed that during high tide events, sediments are transported and deposited in coastal regions, resulting in the buildup of sediment layers and pave the way for solid fraction increase or else compaction to give rise to low hydraulic conductivity. The interplay of currents, tidal forces, and significant wave heights is instrumental in facilitating sediment accumulation. It was found that these hydrodynamic factors contribute to the transport and deposition of sediment.

Compaction of sediment:

The degree of compaction in coastal soil is a determinant of stability. The compaction of sediment layers was a significant outcome of this research. It was evident that as sediment accumulates, the weight of heavier sand settling on top of the existing layers leads to compaction. This compaction process was found to reduce the porosity and hydraulic conductivity of the sediment.

In the case study at hand, sediment accumulation is a prominent phenomenon in the specified region. As sediment layers accumulate atop one another, compaction ensues as a response to the weight of the overlying material. This process results in a more compacted soil structure, which, in turn, leads to lower hydraulic conductivity, setting the stage for a reduced capacity for water to percolate from the landward to the seaward side.

Solid fraction:

Understanding the solid fraction is indispensable in the context of CFS. I was found that solid fraction influences several aspects of landslide behavior:

Density: A higher solid fraction indicates a denser landslide, which possesses greater momentum and potential for damage.

Mobility: The mobility of a landslide is its ability to move or flow. A higher solid fraction often leads to decreased mobility. This is due to the fact that more solid material within the landslide increases internal friction, which resists movement. In the case of Amity Point, the mechanism of sand movement involves hydraulic forces that differ between the landward and seaward sides. These forces contribute to the breaking apart of the sand mass, with the fragments then moving seaward..

Fluidization potential: Conversely, landslides with lower solid fractions, particularly those involving fine-grained sediments like Amity Point, are more susceptible to fluidization, transforming the solid material into a flow with increased mobility and runout distance.

Soil hydraulic conductivity:

The investigation of this study revealed that the compacted sediment layers exhibit low hydraulic conductivity, particularly after periods of sediment accumulation. This characteristic of the soil impedes the flow of water into the ocean during the tide's recession, hindering the natural equilibrium of groundwater infiltration.

Internal angle of friction:

In the context of CFS, the internal angle of friction is a critical geotechnical parameter that characterizes the shear strength of sedimentary materials. It is the angle, measured from the horizontal plane, at which a material can sustain itself without undergoing shear failure. This angle is a direct measure of the frictional resistance within the sediment and is intrinsic to the stability of coastal slopes.

In the specific case of Amity Point, the internal angle of friction plays a significant role in the mechanism of sand movement. The hydraulic forces acting on the landward

and seaward sides of the coastal region are differentially applied to the sand mass. These forces are responsible for the disaggregation of the sand mass, which is a precursor to the movement of sand fragments towards the sea.
The high internal angle of friction at Amity Point means that the sand possesses a greater resistance to movement under normal conditions. However, when the hydraulic gradient is altered by tidal fluctuations, the forces exerted on the seaward side can overcome this frictional resistance. As a result, the sand fragments are mobilized and transported seaward, contributing to the dynamics of CFS.

Coastal Flow Slides:
One of the significant implications of reduced hydraulic conductivity was observed in the coastal flow slides. As the soil's ability to allow water to pass through diminishes, it becomes susceptible to breach. This research documented instances of coastal soil fragmentation and its subsequent transportation into the sea.
These factors include tidal movements, sediment deposition and compaction, the internal friction angle, hydraulic conductivity, groundwater level fluctuations, and sediment accumulation. Sediment accumulation influence leads to steeper slopes and increased solid fraction, creating conditions that are highly susceptible to CFS occurrence. A thorough comprehension of these interconnected phenomena is crucial for coastal management and engineering strategies, as it highlights the inherent susceptibilities and obstacles that coastal areas encounter in response to tidal changes. The insights gained from these findings are instrumental for advancing research in this domain, providing a foundation for the informed and resilient development and preservation of coastal zones, particularly in light of the ongoing challenges posed by sea-level rise and changing environmental dynamics.

5.5 Hybrid Model Prediction and Sensitivity Index Validation

This chapter presents a comprehensive analysis of the empirical findings obtained through the application of a diverse set of research methodologies aimed at understanding the complex dynamics of CFS at Amity Point. This investigation employs what is referred to as a hybrid model, which integrates various approaches including experimental studies, site inspections, the development of a sensitivity index, and the utilization of Bayesian networks. An integral outcome of this study is the establishment of a Bayesian Network model, which serves as a probabilistic framework for assessing the risk of CFS. The model is constructed and refined using the data gathered from high tide fluctuation analysis, groundwater level monitoring, hydraulic gradient assessment, sediment accumulation studies, slope influence analysis, soil compaction exploration, and the determination of internal friction angles. This chapter details the systematic collection and analysis of data, which underpins the development of the Bayesian Network, providing a robust tool for the risk assessment of CFS.

- A risk assessment matrix for coastal flow slides established. The matrix considers a variety of factors, including coastal beach slope, SLR, internal angle of friction, solid fraction, SWH, mean particle size, Shore(ACER), hydraulic conductivity, tidal range (Figure 5.6). These findings were classified according to their significance and summarised in detail in Table 4.1and

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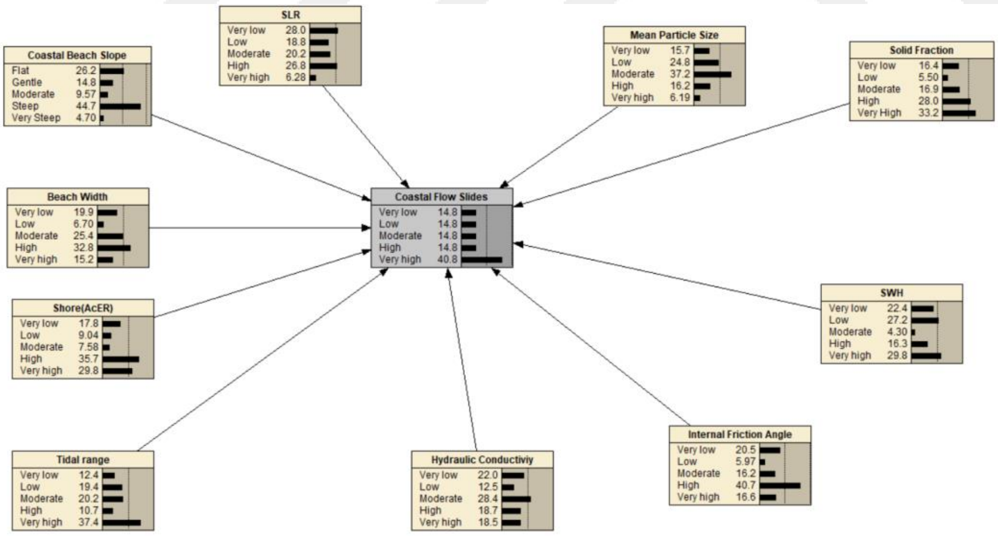

Figure 5.6 : Established Bayesian Network in the hybrid model.

The Bayesian network (BN) can be used to calculate the probability of a coastal flow slide occurring at a given location. This information can then be used to develop risk mitigation strategies.

Figure 5.6 depicts the interrelation between a multitude of components influencing the stability of a coastal flow. Those criteria include:

As can be seen from the BN in Figure 5.6, the stability of CFS is strongly contingent on coastal beach slope, sea level rise (slr), beach width, tidal range, significant wave height (swh), hydraulic conductivity, shore(acer), mean particle size, internal frcition angle, solid fraction.

Experimental studies and site inspections also demonstrate the interplay of factors like internal friction angle, beach slope, tidal range, and sediment properties in determining CFS. That is why, BNs offer a valuable tool to corroborate these findings. By constructing a BN that mirrors these identified relationships, we can simulate scenarios and observe how the predicted instability aligns with both controlled experimental outcomes and the complex dynamics observed in on-site inspections. This convergence between the BN model and both empirical and observational data reinforces the BN's validity as a tool for understanding and predicting CFS, ultimately aiding in decision-making for coastal protection.

The DSI investigated the sensitivity of specific parameters (P1 through P7) in relation to their influence on the breach and liquefaction of a given structure. Table 4.1 contains four different cases, each represented by a different model (CRBF or LFS), and displays the DSI values for each parameter, indicating their relative importance in determining the likelihood of breach or liquefaction. The major equation for each model is also included, representing the relationship between the parameters and the probability of breach or liquefaction. The results of the BN model are tabulated in Table 5.4. The hybrid model results presented in Table 7, show the predicted probability of breach or liquefaction based on the analyzed parameters by BN.

The combined procedure that was followed in this paper is named as the Hybrid Model, and it was used consistently throughout the process. This was conducted by constructing the BN in the simplest and most effort-effective manner for feasible computations.

The combined procedure that was followed in this paper is named as the Hybrid Model, and it was used consistently throughout the process. This was conducted by constructing the BN in the simplest and most effort-effective manner for feasible computations.

As can be seen from the BN, the stability of CFS is strongly contingent on dredging rate, beach slope, packing type (densely packed sand, loosely packed sand), internal angle of friction, and solid fraction. If the coastal slope is enough onset of CFS is, then it is referred to as Retrogressive Breach Failure. On the other hand, the LF will take place by the situation unless the mild-slope is commanding. In the context of coastal engineering, particularly when examining the dynamics of CFS, it is critical to recognize the simultaneous presence of specific parameters as a prerequisite for the initiation of CFS events. The interplay of these parameters is not merely additive but rather synergistic, necessitating their concurrent manifestation to trigger the geophysical process in question. This assertion underscores the complexity of the conditions under which CFS can occur, highlighting the importance of a comprehensive understanding of the contributing factors and their interdependencies.

If the slope condition has a predilection towards CRBF, then the angle has to be somewhat steep, as was indicated in Table 5.4. Figure 5.6 illustrates that the angle of the beach is generally a mild slope because of this reason. This indicates that the slope is not steep enough to generate CRBF; nevertheless, the liquefaction flow sliding rate as a percentage is rather high at 41.5.

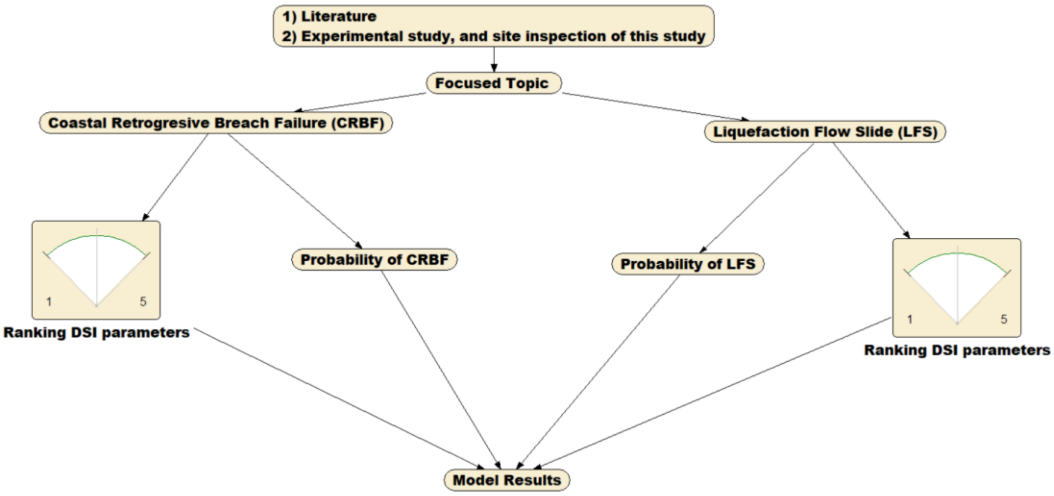

Figure 5.7 : Flowchart for the validation of the hybrid model.

Figure 5.7 presents a schematic representation of a novel hybrid Coastal Flow Slide (CFS) model developed within this study. This model's primary goal is the differentiation between breaching and liquefaction failure modes, and their distinct components. The model is divided into three parts:

Literature: This section lists the relevant literature on CRBF and liquefaction flow slide (LFS) failures.

Focused Topic: This section focuses on the CFS model and its parameters by researchers. Then, probability of each hazards were calculated. These paper were discussed in the literature review (see literature review section).

Model Results: This section shows the results of the CRBF model, including the probability of CRBF and LFS failures, and the ranking of the most important DSI parameters.

Table 5.4 : Model results verification with the literature (DSIP: DSI parameters).

Researchers	Focus	Major Equation	Hybrid Model Results
(Alhaddad et al., 2020).	CRBF	$\frac{k_{BF} \cdot P(V_{\text{breach}})}{k_L \cdot P(V_{\text{liquefaction}})}$	CRBF
(van den Ham et al., 2023)	CRBF	$\frac{k_{BF} \cdot P(V_{\text{breach}})}{k_L \cdot P(V_{\text{liquefaction}})}$	CRBF
	LFS	$\frac{k_L \cdot P(V_{\text{liquefaction}})}{k_{BF} \cdot P(V_{\text{breach}})}$	LFS
(Beinssen et al., 2015).	CRBF	$\frac{k_{BF} \cdot P(V_{\text{breach}})}{k_L \cdot P(V_{\text{liquefaction}})}$	CRBF
(De Groot et al., 2012).	LFS	$\frac{k_L \cdot P(V_{\text{liquefaction}})}{k_{BF} \cdot P(V_{\text{breach}})}$	LFS
Durap et al., (2023)	CRBF	$\frac{k_{BF} \cdot P(V_{\text{breach}})}{k_L \cdot P(V_{\text{liquefaction}})}$	CRBF

6. DISCUSSION

This thesis offers a significant contribution to the underexplored theoretical, experimental, practical, and applied framework of coastal flow slides by introducing the DSI and a hybrid model incorporating BN, ES, and SI components.

These forward-looking methods offer a more nuanced understanding of risk factors associated with CFS and align with the emphasis in previous studies on the need for innovative assessment and management of coastal hazards.

The findings presented in this PhD thesis provides a comprehensive analysis of the factors influencing coastal flow slides. The results indicate that a combination of environmental and geotechnical parameters must be present at a time to trigger coastal flow slides. Among the most influential parameters are tidal range, steep slope, mean particle size, internal angle of friction, significant wave height, currents, and solid fraction. Each of these parameters plays a critical role in the initiation and development of coastal flow slides, and their interplay determines the likelihood of such events.

Interpretation of the results reveals the interdependence of these factors, where the simultaneous presence of multiple conditions is necessary for coastal flow slides to occur. Such as:

i. Tidal range and hydraulic gradient

The tidal range is a significant factor as it can establish substantial forces that, in conjunction with increased groundwater levels, directly influence the hydraulic gradient. A high tidal range can create a steep hydraulic gradient, exerting greater force on the coastal slope and potentially leading to destabilization. However, the impact of the tidal range is moderated by the hydraulic conductivity of the soil. If the hydraulic conductivity is high, water can flow easily from landward to seaward, reducing the risk of coastal flow slides. Conversely, low hydraulic conductivity can impede water flow, increasing the likelihood of slope failure.

ii. Sediment accumulation, slope steepness, and sediment charcteristics

Sediment accumulation is a critical process that contributes to the steepness of the coastal slope. The completion of this process results in a steeper slope, which is more susceptible to flow slides. The mean particle size of the sediment also influences slope stability, with specific ranges such as $D50 < 0.15$ and $D50 < 0.1$ being particularly relevant. The internal angle of friction, with ranges between 23-28 degrees or greater than 36 degrees, further affects the soil's resistance to shear stress and its ability to withstand environmental forces.

iii. Solid fraction and soil stability

The solid fraction of the soil, defined by the range $\Phi_{crit} < \Phi < \Phi max$ ($\Phi_{max} = \pi/(3\sqrt{2}) \approx 0.74$, $\Phi crit=\pi/(3\sqrt{3}) \approx 0.60$, $\Phi crit < \Phi < \Phi max$, is another determinant of coastal flow slides. This parameter reflects the packing density of the soil and its permeability. A solid fraction within the specified range indicates a soil composition that is prone to instability when subjected to the forces generated by tidal fluctuations and hydraulic gradient action.

iv. Significant wave height

While significant wave height itself may not directly trigger coastal flow slides, it plays a pivotal role in shaping the sedimentary environment along coastlines.

The energy imparted by waves to the coastal zone is a primary driver of sediment transport. In areas where significant wave height is consistently high, the increased wave energy can lead to enhanced erosion of coastal features and the mobilization of sediments. These sediments can then be transported and deposited in adjacent areas, leading to the accumulation of sediment and the gradual formation of steeper slopes underwater.

The process of sediment accumulation and slope formation is influenced by several factors, including the direction and intensity of wave action, the grain size and composition of the sediment, and the topography of the seabed. Over time, the accumulation of sediment can lead to the development of slopes that approach or exceed the angle of repose for the sediment type, creating conditions conducive to the initiation of flow slides.

It was found that the interplay between wave energy, sediment characteristics, and coastal topography determines the susceptibility of a region to flow slides. Advanced modeling approaches, as in this study, offer valuable tools for assessing this susceptibility and informing coastal management strategies. Further research into the mechanisms of sediment accumulation and slope stability in coastal zones is essential for enhancing our understanding of coastal flow slides and improving our ability to predict and mitigate their impacts.

v. Interdependence of parameters

The research underscores the interdependence of the identified parameters. For coastal flow slides to occur, not only must the tidal range be sufficient to generate strong forces, but the soil must also have low hydraulic conductivity, a completed sediment accumulation process leading to a steeper slope, a mean particle size within the critical ranges, an internal angle of friction that indicates susceptibility to shear stress, and a solid fraction that suggests potential instability. The absence of any of these conditions can prevent the occurrence of coastal flow slides.

By quantifying the influence of key parameters on CFS through SI and ES, influential parameters affecting CFS were systematically evaluated. This data-driven approach enabled the creation of a customized DSI, which was then coupled with a BN for probabilistic modeling of CFS-prone areas.

The development of the DSI within the hybrid model framework is a significant advancement in the field of coastal hazard evaluation. It enables the pinpointing of coastal areas most at risk of CFS by effectively combining ES and SI. This comprehensive tool is designed for evaluating coastal hazards and assessing the susceptibility of regions to the variables contributing to CFS, thereby facilitating more informed decision-making in coastal risk management.

The initiation of coastal flow slides is a complex phenomenon that requires the simultaneous presence of multiple environmental and geotechnical factors. The research contributes to the understanding of coastal geomorphology and provides valuable insights for predicting and mitigating the risks associated with coastal flow slides. This study focused on the interactions between these parameters and their collective impact on coastal stability, as well as the development of models that can accurately forecast the occurrence of flow slides under varying environmental conditions.

This study encapsulated in this thesis addresses the critical knowledge gap in the study of coastal flow slides. The introduction of the DSI, alongside the hybrid model that synergizes BN, ES, and SI, provides a significant contribution to the coastal engineering field. This thesis not only contributes to the academic understanding of coastal flow slides but also offers practical tools for coastal engineers and managers to better predict and mitigate the risks associated with these events.

7. CONCLUSIONS

Coastal flow slides are complex geological events that pose a significant hazard to coastal communities, infrastructure, and ecosystems. The study outlined in the given research provides a valuable overview of the causes, processes, and potential impacts of these events.

This study investigated the dynamics and mechanics of CFS with a multi-faceted methodology that integrates laboratory experiments, field data collection, computational modeling, and the development of a BN and DSI. The study was centered around Amity Point, leveraging its unique geological and environmental conditions to elucidate the factors contributing to CFS and to develop predictive models and risk assessment tools.

Key Findings:

Sediment and Hydraulic Properties: The interplay between sediment characteristics and hydraulic conditions has been a focal point of this study. Through laboratory experiments and field measurments complemented by rigorous field data collection, this research underscored the paramount importance of sediment properties such as grain size distribution, hydraulic conductivity, solid fraction, and the internal angle of friction. These properties, in conjunction with dynamic hydraulic conditions including tidal fluctuations, groundwater levels, and hydraulic gradients, have been shown to critically influence the stability of coastal slopes and precipitate the initiation of CFS.

These key findings from both field and experimental study, consequently, provide a fundamental framework for comprehending the complex relationship between sediment properties and hydraulic conditions, elucidating the mechanisms underpinning the onset of CFS. Additionally, the inputs that played a significant role in CFS were used to establish predictive models for these events:

i. Bayesian Network: The development and application of Bayesian Network provided insights into the probabilistic relationships between various environmental factors and the occurrence of CFS. These models were instrumental in predicting significant wave heights and assessing the risk of CFS.

ii. Sensitivity Index Development as a metric: The formulation of the DSI as a novel tool for assessing the susceptibility of coastal areas to flow slides presented a quantifiable measure for identifying areas at risk. The DSI incorporated critical factors such as shoreline erosion/accretion rate, tidal range, slope, mean particle size, significant wave height, solid fraction, and the number of coastal structures.

iii. Risk Assessment Matrix: A comprehensive risk assessment matrix for CFS was established, incorporating coastal beach slope, solid fraction, internal angle of friction, tidal range, and other pertinent factors. This matrix is a valuable tool for coastal management and engineering, offering a structured approach to evaluating and mitigating the risks associated with CFS.

iv. Hybrid Model Validation: The hybrid model, combining the BN and DSI, was validated against literature, experimental findings, and field investegations, demonstrating its effectiveness in predicting and assessing the risk of CFS. The model's predictions aligned with observed patterns and provided a robust framework for understanding the complex dynamics leading to CFS.

This study, through its potential to significantly advance the ability of this hybrid model to predict and mitigate the risks associated with CFS events, holds the promise of transforming preparedness and response strategies in areas prone to CFS, ultimately leading to improved safety measures, reduced infrastructure damage, and a more sustainable built environment. The implications of this study extend beyond the case study of Amity Point, offering a paradigm that can be adapted and applied to other coastal regions confronted with similar geohazards. The methodologies and tools developed through this research have the potential to revolutionize the way coastal hazards are assessed and managed, fostering enhanced preparedness, improved safety measures, and more sustainable coastal development practices.

7.1 Recommendations for Future Research

Given the potential influence of climate change and sea-level rise on coastal flow slides, future research should explore the interactions between these factors and flow slide occurrences. This includes investigating how changing climate patterns and rising sea levels may impact the frequency and intensity of flow slides.

Investigation of innovative engineering solutions for mitigating the hazards posed by coastal flow slides. This includes exploring methods for stabilizing slopes, protecting infrastructure, and preserving coastal ecosystems.

Prioritizing the collection of extensive and accurate data related to coastal flow slides, including displacement surface characteristics, geological attributes, climate data, and historical events. This data will facilitate more precise risk assessments and model validations.

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