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Scope for Sustainable Soil Stabilisation in SIDS: Mauritius Case Study

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Abstract— **Soil stabilisation is crucial to tackle the problem of land disasters, such-as landslide, slope failure, and debris flow among others, which may occur naturally or as a result of human actions. Many people are displaced from their homes and some even lose their life in such disasters. Mauritius has not been spared by these major issues and, as a Small Island Developing State (SIDS) which is found under the tropics, the island is at a high risk of cyclones and torrential rains which may induce further land disasters. Another problem occurring worldwide is the landfill scarcity to dispose human, commercial, and industrial solid waste. The facilities for recycling municipal solid waste (MSW) in the country are very limited. Chemical stabilisation could potentially help solve both issues by combining binders with waste products to stabilise the soils in landslide-prone areas. The goal of this paper was to investigate the scope for an economically, environmentally, and socially sustainable solution to help mitigate the negative geotechnical events which come with climate change and also reducing the environmental problem of disposal and landfill scarcity. It was found that plastic wastes (14% of MSW), textile wastes (6% of MSW) and glass wastes (3% of MSW) in Mauritius were largely unrecycled and could partially be used in soil stabilisation.**

Keywords— Soil stabilisation, landfill scarcity, municipal solid waste (MSW) management, sustainable materials.

I. INTRODUCTION

Global warming is the product of excessive use of fossil fuels and deforestation, which, in turn, caused an increase in greenhouse gases, causing abnormal increase in the earth's temperature, known as global warming projected to rise by 1.4°C -5.8°C by the year 2100 [1]. The disproportionate impact on SIDS, as minor contributors to the phenomenon, is often contrasted with their comparatively limited capacity to respond to the climatic challenge when their physical existence is threatened by the subsequent rise of water levels [2].

A recurrent problem arising with increased earth temperature - thus increased precipitation - is the occurrence of geological disaster events such as landslides, rockfall, debris flow and slope failure among others [3][4][5]. SIDS also have an increasing problem of municipal solid waste (MSW) management which adds to the issue of adaptation and mitigation to climatic change [6]. Adaptation to climate change in SIDS will involve interdisciplinary and long-term involvement of stakeholders [1][2]. This research explores the interdisciplinary combination of sustainable geotechnical, chemical, and civil engineering in an attempt to tackle those two problems among other problems caused by climate change. Mauritius island, being one such SIDS in the Indian Ocean, has been taken as a case-study for this research.

A. Geotechnical Disasters

The mean land surface air temperature has increased by 1.5°C since the 1850's and it is estimated that by 2050, there will be a rise of temperature by 1.5°C to 2°C which will induce more rainfall events in the coming century [7]. Ground water levels and frequent flood water cause the moisture level in soils to change suddenly and cause damages in lands, structures, slopes, roads and other infrastructure [8]. A correlation between slope failure events and climatic conditions can be drawn using multiple occurrence factor; however, it is less reliable for first-time slope failures to be used as an indicator since the triggering factor is more difficult to establish as compared to re-activated, accelerated and existing moving slope failures [4][9].

On top of the climatic conditions, other main instability triggering factor is human activity, including degradation of land and vegetation, deforestation, excavation, slope alteration, urbanisation, agricultural practices, disturbance of natural drainage and water bodies, and the construction of heavy structures among others [4]. The world population has increased 40 times since 1900, and a link can be made between the demographic change and the increase in natural calamities including slope failures[4][10][11][12].

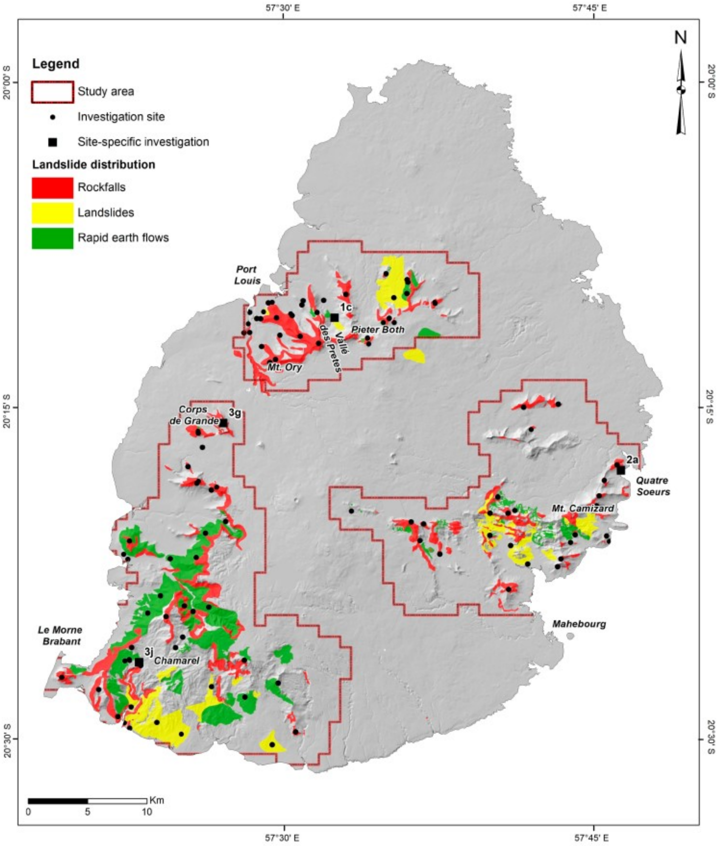

Fig. 1. Active geological movement sites around Mauritius. (Marsala et al. 2019)

Mauritius has several active geological movement sites typically located around mountainous and hilly areas, which can be grouped into 3 main zones as shown in Fig. 1 [3][13]. These sites include both natural and man-induced slope disasters; Natural slope disasters are usually caused by climatic conditions, while man-induced slope disasters are mainly due to inadequate construction in risky areas along with deforestation [3]. In 1978, Varnes has classified the land disasters into 'fall, topple, rotational sliding, translational sliding, lateral spreading, flow and other complex' forms of earth movement [14]. However, the geological disasters in Mauritius may be classified into the following four main types:

1) Landslide – This is a phenomenon generally triggered by heavy rain, river erosion and earthworks, whereby a mass of soil moves downwards on one or more slip (failure) surfaces. The slip surfaces may go very deep underground[3].
2) Slope failure (shallow landslides) – In this event, the mass of soil detaches form slopes with steep angles along a low-shear displacement surface to move relatively quickly at a small distance. Slope failures include natural slope failure, cut-slope failure and embankment failure among others and may generally be classified as surface failures. In less acute cases, ground deformation may be observed at the failure sites [3].
3) Debris flow – This is a disaster where unstable sediment (soil and rocks) along high inclination slopes are liquefied by heavy precipitation and/or high underground water table to flow rapidly downstream [3].
4) Rockfall – Foliated rocks, gravel and boulders topple down a slope in this event due to loose rocks and cracks in the bedrock [3].

B. Landfill Scarcity

SIDS typically face the problem of effective MSW management due to the lack of technical and financial means along with land scarcity for proper disposal of wastes. Most SIDS do not have a sanitary landfill [15]. However, Mauritius possesses a landfill at Mare Chicose where an exponential increase in disposal over the years can be observed as shown in TABLE I [18]. Mauritius has a population of 1.3 million inhabitants with increasing amount of MSW, rising from 0.8 kg/capita in 2002 to 0.9 kg/capita in 2011 [6][16]. The country has inadequate waste recycling capacity where only 13% of waste is recycled [17][18]. The landfill disposal increased from 45,100 tonnes in 1997 to 543,200 tonnes in 2018, i.e. 12-fold increase in 21 years [18].

TABLE I. WASTE DISPOSAL CAPACITY AT MARE CHICOSE LANDFILL IN MAURTIUS.

Year	Waste Disposed (tons)
1997	45,100
1998	157,500
1999	245,700
2000	302,000
2001	346,300
2002	374,200
2003	376,200
2004	386,000
2005	417,700
2006	394,100
2007	394,400
2008	400,800
2009	419,300
2010	427,700
2011	414,500
2012	387,900
2013	429,700
2014	416,800
2015	448,100
2016	443,500
2017	482,200
2018	543,200

II. PROSPOSED MITIGATION STRATEGY

The proposed solution is both an adaptation to climate change and a mitigation strategy to land disasters and landfill scarcity. Soil stabilisation is the answer to these specific problems. There are three main forms of soil stabilisation which may be classified as physical/mechanical stabilisation, chemical stabilisation and biological stabilisation [19][20][21]. Physical/mechanical stabilisation comprises mainly of compacting the existing soil in situ, vertical drain installation, and lowering of water table to enhance its strength [19][20][21]. Chemical stabilisation, on the other hand, is the mixing in of external substances which will react with the in situ soil to change its properties; biological stabilisation mainly includes planting of specific plants which will hold the soil together with the help of their root systems; however, this is only applicable for shallow slope failures since roots have a limited depth reach [19][20][21].Chemical soil stabilisation aims at reducing the plasticity of the soil, minimising moisture-change-induced volumetric changes, while increasing its tensile and shear strength, and improving its stiffness. It is a cost-efficient, environmental-friendly and has high stability performance with long lasting durability; the modification happens at a particle level where soil particles will combine with the chemicals to form a stabilised compound [13][22][23].

Chemical stabilisation of soils involves a chemical and aggregates which will be mixed with the soil to enhance its properties, giving protection against slope failure and subgrade failure [13][24][25][26][27]. Soft soils are not strong enough to support structures, especially those with heavy traffic added to the dead load of the structure, causing premature failures which may lead to accidents. Under high water content, peats deform greatly and weak soils tend to cause stability issues during construction and excessive settlement post construction. Expansive soils, on the other hand, cause swelling and shrinkage due to changing moisture levels [13][24][25][26][27]. Coarse-grained soils are less compressible as compared to fine-grained soils in general. Soil grading, plasticity, liquidity, and workability may be enhanced by this method, improving the structural strength and durability [13][28].

Chemical soil stabilisation is traditionally carried out in form of wet soil mixing (WSM), which involves wet chemical binder injection into soft clays and soils with low water content, while dry soil mixing (DSM) is used for soils with high water content, where a powder is injected with drills [20][29]. The dry powder in DSM reacts with the water in the soil itself and reacts to form rows of soil-binder mix columns of up to 20 m, while in WSM, the wet slurry chemical mixes with the dry soil to form columns of up to 30 m depth. Shallow soil stabilisation involves chemical stabilisers mixed with the soil up to 4 m deep using excavators with attached mixing tools [20][29].

Traditional binding agents such as lime and cement can be added to soil to improve its geotechnical properties, increasing its strength and stiffness durability, while decreasing its swelling/shrinkage potential and plasticity. But there are certain drawbacks: sulfate-rich soils react with the calcium and aluminum present in those binding agents, causing subsequent failure of pavements laid on those soils [20][30]. Moreover, the traditional stabilisation methods are not sustainable due to the production methods of cement and lime which are very detrimental to the environment; it not only causes air pollution but is depleting a finite resource through quarries to get the raw materials required to produce those stabilisers [13][31][32][33]. A very large quantity is required for chemical soil stabilisation to be effective, and the curing time is very lengthy. Another side effect is the brittleness of those soils once solidified and soils with high sulphate contents tend to expand and contract with those additives. These properties make traditional soil stabilisers unsustainable [13][31][32][33].

A sustainable stabiliser must meet the three key criteria of sustainability, that is, being environmental-friendly, economically profitable and socially benefic [35]. The proposed method of soil stabilisation is a combination of binders and MSW that are generally complex and costly to be recycled as partial fillers with minimum processing. Using the inorganic MSW as partial fillers will significantly reduce the amounts of chemicals to be used, thus leaving less carbon imprint through unclean production of such binders [13][31][32][33].

III. RESEARCH METHODS

The idea of multi-disciplinary action to mitigate both of the problems of geotechnical disasters and landfill scarcity is to potentially use the maximum inorganic wastes of the disposed MSW, with minimal processing, in the chemical soil stabilisation of areas prone to geotechnical disasters. Soil stabilisation is of critical importance in tackling the geotechnical disasters. The possibility of using non-organic wastes as partial fillers in soil stabilisation was investigated by conducting a product availability study of disposed wastes in Mauritius, the amount currently being recycled and the constraints associated with using those waste products in chemical soil stabilisation.

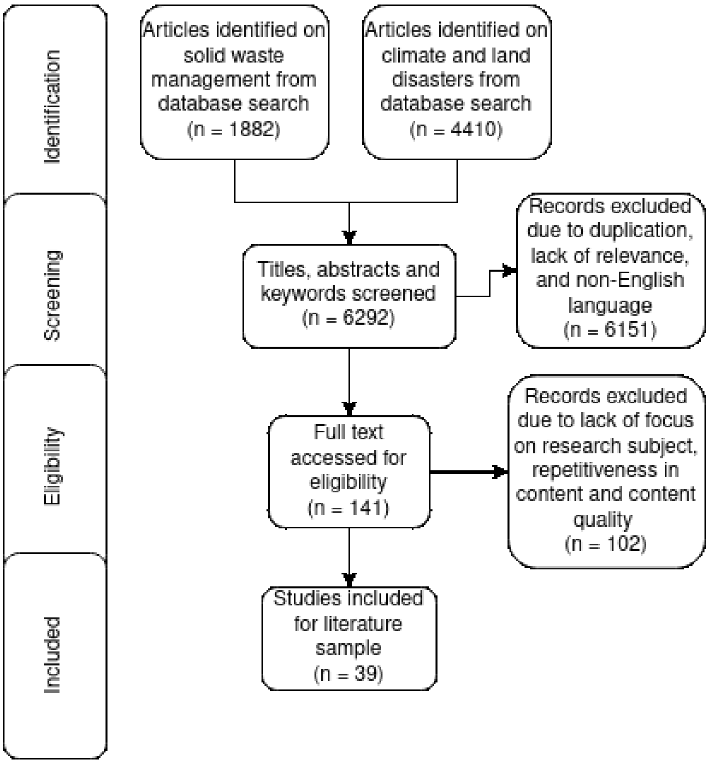

Fig. 2. Flow diagram of the study.

A content analysis of available literature on MWS data was performed. A 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) approach was adopted for this study. Although this topic is very broad, mainly the peer-reviewed journals were considered through various library databases. However, due to the specificity of the case-study, some information were also taken from Mauritian government data, policies and environmental reports. While research in the field is rapidly evolving, some older articles remain still relevant and unchanged to this day. Thus, no specific timeline on article publication year was retained.

Identification criteria depended on the keywords: Municipal Solid Waste (MSW) management, climate change and it's subsequent effect on land disasters (variation: geological disaster, landslide). 1882 articles on solid waste management and 4410 articles on climate and land disasters were identified as shown in Fig.2. The screening criteria depended on the presence of duplicate articles, articles in different languages other than English language and a lack of relevance in the abstracts. All the 6292 articles were screened for their titles, keywords and abstracts, out of which 6151 articles were filtered out. The remaining 141 articles were accessed in full text for eligibility. The eligibility criteria was based on the amount of focus on the specific subject of this study, repetitiveness of content in similar articles and content quality, where 102 articles were rejected. Thus 39 articles were retained and included in this research.

III. RESULTS and DISCUSSION

It was found that out of the solid wastes disposed, the inorganic MSW which may be used as soil stabilisation fillers are plastics, textiles and glass which consist of 14%, 6% and 3%, respectively. These can be ground to particles, or used as fibres and added to binders. The textile wastes however consist both of organic and synthetic materials. Organic textile materials is not good for long-term stabilisation as they would decompose underground. The synthetic waste materials such as nylon fabric waste have to be collected separately from the factories and used for soil stabilisation [37]. Food wastes, yard wastes and paper wastes also decompose easily under the soil and thus would be inappropriate as chemical soil stabilisation fillers [37][38]. Metals on the other hand are precious materials which would be uneconomical to be used as filler material and should rather be recycled. Moreover, some metals such as iron would oxidise and breakdown under the soil, making it a non-durable stabilisation [38].

TABLE II. WASTE DISPOSAL IN MAURIIUS

MSW	Proportion (%)
Food Wastes	27
Yard Wastes	27
Paper	14
Plastics	14
Textile wastes	6
Glass	3
Metals	3
Others	6

Fig. 3. Sustainability triangle for sustainable soil stabilisation using MSW.

Pursuing further in-depth research in combining MSW in geotechnical soil stabilisation while also focusing on waste segregation at source and adequate waste collection system may prove to be a game-changer for Mauritius and SIDS in general. Segregation at source will allow minimal processing of wastes before use as stabiliser filler since there will be no further need to separate the relevant wastes from irrelevant wastes in a dedicated waste segregation facility. The three criteria for sustainability will be met as shown in Fig. 3. In terms of environment, this project will contribute towards an increase in the safety of slopes and risky geotechnical areas, while reducing the problem of landfill scarcity. With regards to the economical aspect, it will benefit the SIDS by providing a relatively inexpensive solution to geotechnical disasters; a new life-saving product will be manufactured from waste products with minimal processing, thus minimal cost. Socially, the production of such stabiliser will create employment and also the use of this technique will potentially prevent damage of public and private property, loss of life and mass displacement of people from their homes.

This project is in line with the United Nations Sustainable Development Goals (SDGs).The United Nations Department of Economic and Social Affairs (UNDESA) has set 17 SDGs [39] and this project meets with three of those goals as follows:

1) Goal 9 - Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation [39]; Innovation in construction and transportation on unstable soils, while reducing the problem of landfill scarcity for disposal of MSW.
2) Goal 11 - Make cities and human settlements inclusive, safe, resilient and sustainable [39]; Stabilising landslide areas will make the regions safe and resilient for the inhabitants, easing the effects of potential material or life loss and/or home displacement.
3) Goal 13 - Take urgent action to combat climate change and its impacts [39]; This study falls into climate change adaptation as it will result in countermeasures against slope disasters which will occur more frequently due to increased rain precipitation due to climate change.

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