MODELLING FAILURE MECHANISMS OF SOFT CLIFF PROFILES

T. Newson,
Geotechnical Research Centre, Department of Civil and Environmental Engineering, University of Western Ontario, London, Ontario, Canada.
P. Sentenac,
Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, Scotland, United Kingdom (former Leverhulme Fellow on Cliff Erosion at Dundee University)
P. Dong,
Department of Civil Engineering, University of Dundee, Dundee, Scotland, United Kingdom.
X. Wu,
Department of Civil Engineering, University of Dundee, Dundee, Scotland, United Kingdom.
M. Davies,
Department of Civil Engineering, University of Dundee, Dundee, Scotland, United Kingdom.

ABSTRACT

A large proportion of the 11,000 km coastline of the United Kingdom is backed by soft cliffs. These cliffs are subject to frequent slumping and landslip events, particularly where sea and ground water percolates into the soil and rock. Many of these cliffs are formed from glaciogenic sediments, which experience severe erosion and rapid recession with long-term horizontal recession rates typically up to 2-3 m/year. A series of scaled physical model tests have been conducted using a large centrifuge facility with two-dimensional cliff models. These were tested in a wave flume container located on the centrifuge. Wave loading was created using a quasi-flap paddle system that was located at the opposite end of the centrifuge box. A number of tests were conducted using different cliff materials (i.e. combinations of sand and Portland cement). A parametric study was carried out to assess the influence of variations in cliff geometry and height, soil properties, wave amplitude and period. From these tests, it has been found that generally, failures occurred by progressive undercutting of the cliff toe, followed by global failure of the cliff mass.

1. INTRODUCTION

Much of the coastline of the United Kingdom is subject to frequent collapse and landslip events, and cliffs experience severe erosion and rapid recession. Enormous costs are associated with capital expenditure for protecting these cliffs, relocating coastal facilities and the long-term impact of these protection works on adjacent coasts. Hence it is of vital importance to be able to predict future cliff recession accurately. In an effort to provide data to validate numerical analyses, scaled modelling of soft cliff erosion using conventional wave flumes has been attempted by a number of researchers. These studies have employed a range of cliff materials, such as sand and clay mixtures, Portland cement with chalk and crushed gravel, and undisturbed and reconstituted clays. However, there has been considerable doubt as to whether such models are properly scaled, since the stress profiles within the cliff can not be correctly reproduced. Comparisons with field scale failure mechanisms and recession rates have proved to be very poor.

As an alternative, the study described herein consisted of a series of scaled physical model tests using a large centrifuge facility at the University of Dundee. Two-dimensional plane strain cliff models were tested in a wave flume container of internal dimensions 1500 mm x 300 mm x 400 mm, located on the centrifuge. The centrifuge strong box has Perspex sides, so that the model may be viewed from the side during testing. Digital video cameras were used to record soil movements and provide information on the failure mechanisms. Drainage was accomplished using a basal filter system and the internal water table in the cliff was controlled by adjusted by varying the head of water at the base filter. Wave loading was created using a quasi-flap paddle system that was located at the opposite end of the centrifuge box. Internal pore pressures were monitored within the slope using miniature pore pressure and tensiometer devices.
A number of tests were conducted using different cliff materials (i.e. combinations of sand and Portland cement). A parametric study was carried out to assess the influence of variations in cliff geometry and height, soil properties, wave amplitude and period. . Examples of typical results from these tests are given below.

2. SOFT CLIFF EROSION

2.1 Erosion Mechanisms

A large proportion of the seashore UK cliffs areas are protected with a range of engineered structures, many of these were constructed in the Victorian era and are in need of urgent repair. Projected rises in sea level of 650 mm over the next century due to global warming only exacerbate the problems. Other anticipated effects of climate change will be higher, more powerful tides, increased winter rainfall (30%) and higher frequency more violent storms. Hence the rate of erosion of these soft coasts will only increase with time. Cliffs are subject to frequent landslips especially when water percolates into the rock and reduces its effective shear strength.
Variations in the wave climate (wind velocity, duration and fetch), near shore and offshore bathymetry, shore orientation, water level, composition of the cliff and beach materials and any man-made coastal structures are reflected in the cliff erosion rates observed in the field. Laboratory and field testing have linked basal cliff erosion, with notching and cliff instability, and recession of

the heads of the cliffs (Belov et al., 1999). Cliff surface deterioration and basal erosion in particular have been related to the assailing force of incoming waves.
With global warming expected to produce the frequency of large waves, able to carry more abrasive debris and greater force, the prediction and amelioration of this agent is vitally important.

Marine waves have been found to be quasi-periodic and more efficient when high tides coincide with storms, and basal erosion of the cliff face takes the form of notching. Erosion wave mechanisms consist of two main processes that affect the basal part of the cliff. The first mechanism is due to hydraulic action: namely wave breaking, water spray and high speed droplets. The second mechanism relates to the abrasive action of particles that are lifted by turbulent water currents and waves. The hydraulic forces lead to compression, tension and shearing actions of the cliff material. The action of these repeated stresses on the cliff surface are balanced by the strength of the material in the cliff.

The other major consideration for cliff erosion is the global stability of the slope itself. Whilst the cliff slope stability is influenced by the usual aspects, i.e. geometry (height and angle), material properties (strength and density) and the location of the water table, the predictive process is complicated by the evolutionary nature of the slope geometry. In addition to the failure characteristics cliff erosion depends on spatial and temporal scales as some processes can be short term with only weak correlation in the long term. For example cumulative long shore and storm related cross shore processes have different time scales. Unlike many typical slope engineering problems, stability analyses of the most recent profile is of little consequence unless the profile changes over time can be predicted. Hence the rate of change of the geometry is important and requires knowledge of geomorphology, geology, climate and mechanical processes. It has been observed during field tests that there is a tendency for shallow surface failures, toe erosion and face degradation. Adjustment of the cliff slopes to these processes is through deep failures and global slope failures, until the average angle of the slope reaches an ultimate slope angle of approximately 50% of the angle of friction (e.g. Skempton and Delory, 1957).

2.2 Physical Modelling of Cliff Erosion

Scaled physical modeling of soft cliff erosion using conventional unidirectional wave flumes has been attempted by a number of researchers (e.g. Sunamara, 1976; Johnson, 1977; Rohan et al., 1980; Kamphuis, 1990; Skafel and Bishop, 1994). These studies have employed a range of cliff materials that were tested in large flumes: sand, sand and clay mixtures, Portland cement with chalk and crushed gravel, and undisturbed and reconstituted clay.
However, there has been considerable doubt as to whether such models are properly scaled, since the stress profiles within the cliff cannot be correctly reproduced (and hence neither were the soil properties, which are stress level dependent, e.g. undrained shear strength, density, moisture content, etc..) and the size of defects within undisturbed samples would have been too large. Comparisons with field scale failure mechanisms and recession rates have proved to be very poor.

General observations made during these tests suggest that intact field specimens are most resistant than reconstituted samples, erosion resistance of cliffs is reduced if sand or other abrasive materials are present in the waves and erosion, and the erosion tends to initiate in zones of weakness, e.g. fissures, cracks, silt lenses.

If plunging breakers or hydraulic jets occur, the erosion rates of the cliffs are found to be comparable to the situations where an abrasive medium such as sand is present in the waves (Kamphuis, 1987).

Field measurements and modelling by Edil and Vallejo (1980), Sterrett and Edil (1982), Davidson-Arnott (1986), Ollerhead and Davidson-Arnott (1993) and Trenhaile (2000) on erosion in tills around the Great Lakes suggest that the cliff recession is controlled by near-shore erosion, ground water levels and softening of the cliff material over time. Back analysis of the slope evolution using repeated limit equilibrium methods were found to be reasonably successful.
Only a few studies have investigated the effects of wave trains on marine sediments in the centrifuge. Sassa and Sekiguchi (1999) subjected flat sand beds to progressive and standing waves created in a centrifuge mounted wave flume at 50 g with viscous fluid (silicone oil). This provided scaled waves of 0.5 m with 4.5 second prototype wave periods and induced liquefaction of the sand beds.
There have been a number of studies where the important effects of water table variations on slope stability have been investigated. An example is the investigation of riverbank failure by Frydman and Beasley (1976) on kaolin and intact clay samples conducted at 50 g.

3. CENTRIFUGE TESTING METHODOLOGY

3.1 Overview

A number of scaled physical model tests were conducted using different cliff materials. These were simulated in the 7 m diameter (150 g-tons) Dundee centrifuge (shown in Figure 1).
The stability of generic models of soft soil cliffs was investigated subjected to various external loadings, e.g. groundwater table variations and wave loading.
A parametric study that considered the effect of cliff geometry and height, soil properties, wave amplitude and period, and beach angle on the failure mechanisms was conducted.
Homogeneous artificial materials have been investigated initially (silica sand and Portland cement), as a precursor to representations of more complex natural materials that will include defects, or layered materials. Examples of typical results from these tests are given in the paper below.

3.2 Centrifuge Flume and Models

Centrifuge-based physical modeling of fluid transport problems can offer major time-scaling advantages. Thus, pore fluid seepage or erosion process at prototype scale over a period of years can be simulated in a model in a matter of hours.
Two dimensional plane strain soil models were tested in a specially design wave flume container of internal dimensions 1500 mm x 450 mm x 400 mm (shown in Figure 2), which formed the centrifuge strong box. The flume box has Perspex sides, so that the model may be viewed from the side during testing.
Digital video cameras (viewing the side and top of the model) were used to record soil movements (via the use of small side markers and a grid system) and provide information on the failure mechanisms.
Drainage was accomplished using a basal filter system and the internal water table in the cliff was controlled by adjusted the head of water at the base filter.

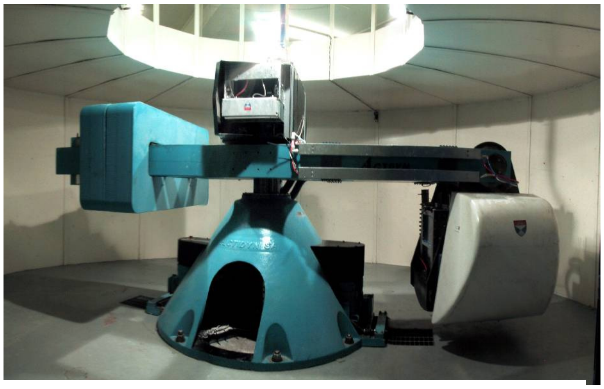

Figure 1. Dundee Geotechnical centrifuge

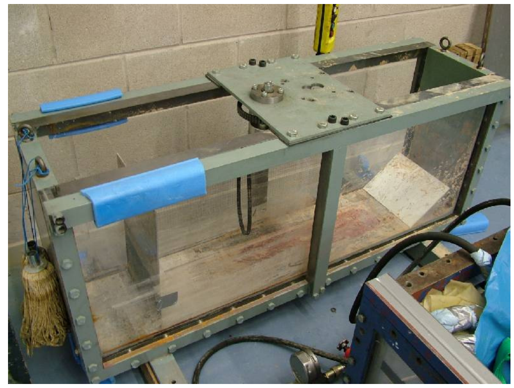

Figure 2. Wave flume container

Wave loading was created using a quasi-flap paddle system that was located at the opposite end of the centrifuge box. Wave probes and pore pressure transducers were used to monitor the wave height and period. Internal pore pressures (and /or suctions) will also monitored within the slope using miniature pore pressure and tensiometer devices. In order to correctly scale the dynamic and diffusive events (Dong et al., 2001) it is required to use a more viscous fluid than water. Some of the later testing has employed metholose like Dewoolkar (1999), however the tests reported herein have used de-ionised water only.

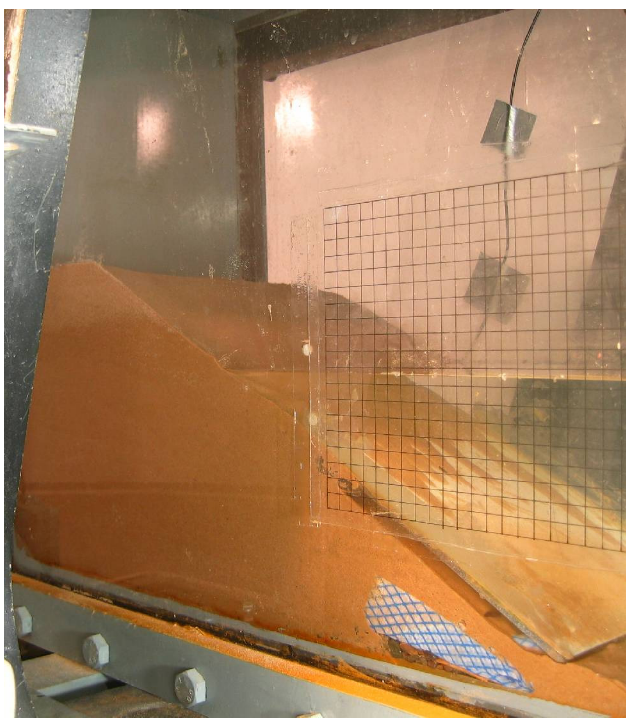

Figure 3. Example sand and cement cliff slope

3.3 Centrifuge Test Procedure

Model cliffs were made using a fine silica sand (known as Congleton sand). This material is uniformly graded with d_{50} = 0.3 mm, G_s = 2.65 and the particles were surrounded. The angle of repose of the loose soil was measured to be 32^o and this is believed to be close to the critical state angle of friction.

The maximum and minimum densities of the sand are 1.78 and 1.39 g/cm^3 respectively. All of the models were mixed at 10% moisture content and placed in the flume box by hand prior to cutting to the required geometry and height.

Additional quick drying Portland cement was added to a number of the mixtures prior to placement at concentrations of 0.5, 1 and 2.5 % (weight for weight).

Cliffs were created with model heights varying from 25-30 cm and slope angles of 30, 45, 60 and 80^o (see Figure 3).

A submerged solid beach with an angle of 8^o was placed in front of each model cliff. Water depths of 16 to 20 cm were also used for the models. Each model was placed in the flume box on the centrifuge and increasing gravity fields (N) from 5 to 50 g were applied. The required water table locations were allowed to equilibrate prior to switching on the wave maker and simulating storms. Additional tests were conducted at other scales/'g' levels to ensure that the assumed scaling laws were correct. The various tests allowed scaled prototype slopes of up to 15 m to be subject to scaled waves of 0.15 to 1.25 m height, with periods from 0.6 to 2.6 seconds with frequencies from 1.31 to 11.9 hertz at 30g equivalent to 0.04 Hertz to 0.397 on a real scale.

4. CENTRIFUGE TEST RESULTS

Three different series of tests by sets of three were carried out, one with pluviated sand forming the cliff, the two others were related to sand and cement
The first set of tests with sand is resumed in the following table 1.

Table1. Centrifuge tests with sand, Cliff and waves parameters

Paddle stroke cm :			2.9		Pluviated sand cliff						
Tests	g level	Hcliff	topx cliff	slope ^{0}	hwater	T wave	Lwave	wave	Notching	F (hz)	F (hz)
		cm	cm	ɵ	cm	sec	m	crest cm	collapse time	(*30g)	real
						2.6	3.39	0.5	gentle after 10 min	1.31	0.044
1	30g	28	15	30	18	1.4	1.74	1	15 min	1.31	0.044
						0.82	0.89	2	17 min	2.65	0.088
						0.62	0.57	3	18 min	2.65	0.088
						1.4	1.74	1	30 min	1.31	0.044
						1.4	1.74	1	45 min one step	3.9	0.130
					break	1.4	1.74	1	49 min	6.6	0.220
						1.4	1.74	1	51 min	7.9	0.263
						1.4	1.74	1	55 min	9.3	0.310
					foam	0.85	0.89	2	56 min	10.6	0.353
						0.85	0.89	2	64 min	11.9	0.397
2	5g	28	30	80	18	gravity	gravity	0	gravity collapse 4'30"	0	0.000
re start				60		2.6	3.39	0.5	Notching	1.31	0.044
						1.4	1.74	1	14 min	2.65	0.088
						0.82	0.89	2	18 min	3.9	0.130
3	30g	25	20	45	16	0.77	0.79	2	1cm after 1 min	1.31	0.044
						0.77	0.79	2	small 5 min	2.65	0.088
						1.3	1.52	1	35min	9.3	0.310
						1.3	1.52	1	45 min	10.6	0.353

Table 1 shows the different time when a partial collapse of cliff occurred. It gives also the properties of the waves created and sometimes the size of the notch before the collapse. When the cliff was too steep at 80^o a gravity collapse took place very quickly during the spin and the time necessary to reach 30g, as indicated in test 2. The cliff had to be cut and re shaped to a slope of 60^o.

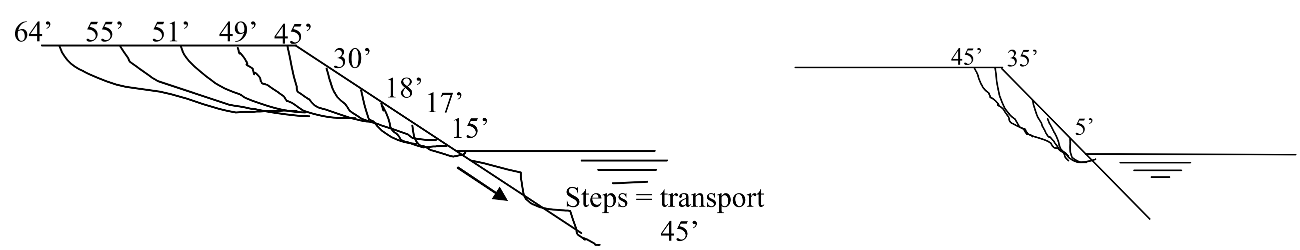

Figure 4.
Sand cliff erosion evolution profile for a 30^o slope and for a 45^o slope versus notching time

In order to get the most efficient erosion, some 2 cm crest waves are created to attack the beach and the toe of the cliff or the joint position, tending to form a stability equilibrium profile of the beach in the angle of repose of the sand material. From this new profile only 1cm crest waves are necessary to carry on an efficient notching. Figure 4 shows the evolution of the profile for the test 1 reported in table 1 for a cliff with a 30° slope and 45° slope. The process started with the cliff face becoming steeper gradually, then, eventually the cliff was so steep that it couldn't be stable any more. A tensile fault was produced on the top of the cliff and the collapse occurred inevitably.
When the wave run-up on the beach was sufficient the debris on the back shore from the previous collapse or the cliff toe (when it was not protected by debris) was eroded. Then the eroded material was removed from the cliff toe.
A second set of tests were performed with Sand and Cement with 10 % moisture content and 1% cement content, followed by a third set at 0.5% cement content presented here in table 2 showing the consecutive times when a partial or total collapse of the cliff happened with the properties of the waves used.

Table 2. Centrifuge tests with cemented Cliff and waves parameters

Paddle stroke cm :			**2.9**		**Cemented cliff (0.5% cement, 10% moisture content)**						
Tests	**g level**	**Hcliff**	**topx cliff**	**slope ^{0}**	**hwater**	**T wave**	**Lwave**	**ha**	**Notching**	**F (hz)**	**F (hz)**
		cm	**cm**	**θ**	**cm**	**sec**	**m**	**crest cm**	**Notching time**	**(*30g)**	**real**
7	30g	28	20	45	16	0.62	0.57	3	15 min	3.31	0.110
7	30g	28	20	45	16	0.77	0.79	2	48 min	2.65	0.088
7	30g	28	20	45	16	0.77	0.79	1.5	2h21	2.65	0.088
					16	0.77	0.79	1.5	3h01-3h04	2.65	0.088
8	30g	28	20	30	16	0.95	1.04	1.5	strong signal	2.65	0.088
						0.77	0.79	2	strong signal	2.9	0.097
						0.77	0.79	2	57min	3.04	0.101
9	30g	30	25	60	20			0	gravity collapse 6'15"	0	0.000
9b	30g	30	22	85	20	1.45	1.9	1	left corner 38 min	2.65	0.088
						1.05	1.29	1.5	58 min	2.9	0.097

The wave action at the toe of the bluff gradually carved into the bluff material, creating a "notch". The erosion caused again an undercutting on the face of the bluff. A clear indicator of cliff erosion is the presence of a notch, a laterally extending hollow at the base of a cliff, its width being greater than its depth.Then the notch is broadened and some tensile joints located on the bluff top appeared announcing an imminent block failure.When the notch reached a threshold depth, the weight of the overhanging bluff couldn't no longer be supported which ultimately lead to a catastrophic collapse of the bluff face with large sand and cement blocks falling down to the beach. The mechanism is showed on Figure 5 in the case reported in table 3 of a cemented cliff with a 30° and a 45° slope.

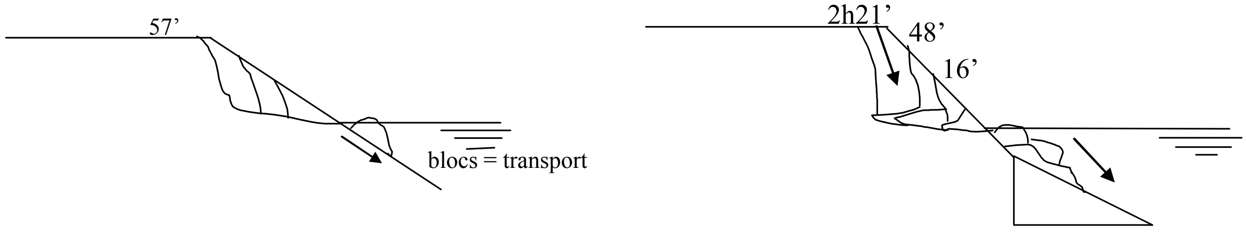

Figure 5. Cliff erosion evolution profile with sand and cement (1%) for a 30° slope and 45° slope

It has to be noted that the tensile fault on the top of the cliff is smaller on the pure sand cliff than the one made of sand and cement.

The notch or undercutting of the toe of pure sand cliff was smaller than the one of sand with cement. The failure mode of the collapse should be a straight fall, but the pure sand cliff was eroded very quickly after the fall. The sand cliff with cement collapsed gradually, generally forming some soil blocks deposited at the toe of the cliff.

As a comparative example with a real cliff, the scaled conversion gives a full collapse of 57 minutes for a 1 % cemented cliff with 45^o slope in the geotechnical centrifuge corresponding to 35 days on the coast, the waves attacking the cliff having a 1.5 cm crest equivalent to 45cm. In the case of a sand cliff with the same slope angle the first collapse occurred only after 15 minutes corresponding to 9 days on the real scale with 30 cm crest waves.

5. CONCLUSIONS

From these tests it has been found that generally, failures occurred by progressive undercutting of the cliff toe, followed by global failure of the cliff mass. The evolution of the cliff profile with successive failure events has also provided some interesting observations, which will also be discussed in the paper.

The study has provided the first result for the generation of a comprehensive database of behaviour and will allow parameterisations to be developed for the numerical modelling phase of the study. The main failure modes such as translational and circular failures will be fully parameterised based on the test results.

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