EXPERIMENTAL BEHAVIOUR OF A COMPACTED SILT USED IN A FLOOD DEFENCE EMBANKMENT IN INDONESIA

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ABSTRACT: A flood embankment in East Java, Indonesia with a recurrent history of geotechnical failure is the focus of this research. The site was visited in May 2006 and this paper describes the study site and presents the relevant in-situ data. Laboratory characterisation of the sampled material was carried out and presented herein are the soil properties, particle size distribution curve and x-ray diffraction results. Soil water retention curves were determined through the use of three different methods: filter paper, tensiometer and pressure plate allowing a comparison of these methods. Four series of oedometer tests were carried out under: (i) dry-of-optimum, (ii) wet-of-optimum, (iii) prepared wet and then dried and (iv) close to optimum initial conditions. Where collapse was observed, the collapse potential for the specimen was evaluated and severity of collapse determined. These preliminary results show the importance of good compaction control at the site and help to explain some failures observed at the site.

Keywords: unsaturated compacted soil, oedometer test, volumetric compression collapse

1. INTRODUCTION

Many unsaturated soils may undergo a significant settlement when wetted under load. If water is readily available then this settlement can occur rapidly; this is known as collapse. There are four main conditions required for collapse to occur: (Barden et al. 1973, Mitchell 1976) (i) an open partly unstable, partly saturated fabric; (ii) high enough total stress that causes the structure to be metastable; (iii) a binding or cementing agent which stabilises the structure when dry and (iv) addition of water. Each of these must be present to produce a collapse phenomenon, the degree to which each is present influences the resulting collapse observed.

Barden et al. (1973) postulated three types of bonding material or force: (i) simple capillary forces between silt-silt and silt-sand bonds; (ii) clay buttresses, where clay plates exist between sand or silt grains and (iii) chemical agents such as iron oxide, or calcium carbonate, often the bonding agent in loessial soils. However in many cases more than one of these types of bonding will be involved in stabilising the unsaturated soil.

Lawton et al. (1989) carried out double oedometer tests using a moderately plastic soil. They reported that the soil exhibited both swelling and collapse depending on the overburden stress; that volume changes were inversely related to initial moisture content as was maximum collapse. Compacting the soil at a moisture content greater than optimum and to a level above a critical compaction value were suggested as two means of eliminating both collapse and swelling behaviour.

Wetting-induced collapse is defined by Lawton et al. (1992) as the densification of a soil caused by the addition of water at a constant total vertical stress. Lawton et al. (1992) highlight the difference between the near surface collapse in naturally deposited soils and the deep-seated collapse of compacted soils. Several case histories regarding the collapse of earth dams are discussed in Lawton et al. (1992), where it is indicated that damage or failure occurred soon after the initial filling of these reservoirs.

More recent research in this area has focused on performing collapse tests using triaxial equipment (Lawton et al. 1991, Pereira & Fredlund 2000) and on the influence of cyclic wetting and drying (Rao & Revanasiddappa 2006).

This paper presents a series of oedometer tests investigating the collapse behaviour of a silt used in flood embankment construction in Indonesia. The oedometer tests are supported by site investigation data and laboratory characterisation of the material including soil properties, particle size distribution and an x-ray diffraction investigation. Furthermore soil water retention curves were determined using three different methods: filter paper, tensiometer and pressure plate, high-lighting the important role of suction under dry of optimum conditions.

At the site under investigation a number of engineering works have been constructed to improve the stability of the embankments. However it is proposed here that these works provide the loading required, alongside the readily available access to water, low densities and moisture contents dry-of-optimum to produce conditions favouring collapse.

2. SITE DESCRIPTION

The soil investigated here was sampled from a site located along the flood defence embankments of the Bengawan Solo River, in the village of Kedunhardjo, East Java, Indonesia. The Bengawan Solo River is the longest river on the Island of Java at 540km, with the source located in central Java and entering the sea, north of Surabaya in East Java.

The river level can vary as much as 10m between the dry and wet seasons (see Fig. 1). The embankment is a 10m high two-step embankment which is frequently overtopped in the rainy season. At this site the Bengawan Solo River is 100m wide. Located to the landward side of the embankment is the village of Kedunhardjo. This village is evacuated each time overtopping of the embankments occur. This is a recurrent problem along the length of the Bengawan Solo River as Java is the most densely populated island in the world, with a population of 124million. As a result many villages have to be relocated during periods of flooding. Not only are there immediate financial consequences but this repeated flooding has negative impacts on local agriculture, particularly reducing crop yields.

Fig. 2 highlights some of the geotechnical problems encountered along the embankments of the Bengawan Solo River. Fig. 2a shows erosion of the natural embankment which runs along one side of the river at this section. It is this eroded material which has been removed from the river bed and used to construct the man-made embankment on the other side of the river. The material can therefore be considered a transported alluvial silt. As such, it is unlikely that a chemical agent provides the stabilising force in the unsaturated condition. Therefore according to Barden et al. (1973) it may be assumed that the bonding forces are due to simple capillary forces or clay buttresses. The natural embankment is in a continual state of erosion and failure; evidence of which was observed along the entire length of the natural embankment. A shallow failure is shown in the man-made embankment in Fig. 2b; the soil investigated was sampled close to this existing failure. Fig. 2c shows a global slip failure which occurred on the gabion reinforced section of the embankment.

Fig. 1. Variation in water level of Bengawan Solo River during (a) wet season and (b) dry season.

This measure put in place by the Ministry for Public works, due to previous failure of the embankment at this location, was constructed during the dry season of 2005. The failure observed in Fig. 2c occurred during the first wet season after this construction, in December 2005. This failure could be attributed to a deep-seated collapse of a compacted fill under heavy loading, after first wetting as described by Lawton et al. (1992). In another location, Fig. 2d, the Ministry installed concrete slabs to act as protection to the slope of the embankment against erosion. Differential settlements and slippage of the slabs have been observed here

The site was visited at the beginning of May 2006, at the end of the wet season, one week previous, the embankments had been overtopped and the village flooded. Sand cone tests were carried out and low in-situ densities were found ranging from 1.18-1.36 Mg/m^3 alongside high moisture con-tents ranging from 36-43%. Dr Ria Soemitro of ITS, Surabaya working in collaboration with the Ministry for Public Works has communicated to the authors that in-situ densities as low as 0.8-1.0 Mg/m^3 have been found along these embankments. Shear vane tests were also carried out and the cohesion ranged from 20kPa to 40kPa, indicating a soft soil as classified in BS: 8004:1986.

Fig. 2. Failures along the Bengawan Solo Embankments: (a) erosion of natural embankments; (b) shallow failure of man-made embankment; (c) global failure of gabion reinforced embankments; (d) differential settlement under concrete protection slabs.

3. LABORATORY TESTS

3.1. Material Properties

The material investigated here was sampled at a depth of 1-1.5m from the crest of the step of the embankment at a location close to a site of previous failure (Fig. 2b). Table 1 presents the material properties for the Bengawan Solo fill. Plotting Casagrande's plasticity chart, the material falls be-low the A-line and can be classified as an inorganic silt of high compressibility. Fig 3 presents the particle size distribution for this material and confirms the large quantity of silt present (47%).

Table 1. Soil Properties

Property	Value
Liquid Limit (%)	53
Plastic Limit (%)	37
Plasticity Index	16
Particle Density (Mg/m^3)	2.49
Sand Content (%)	36
Silt Content (%)	47
Clay Content (%)	17
Mean Grain Size (mm)	0.026
Coefficient of uniformity	40
Max. dry density (Mg/m^3)	1.48
Optimum moisture content (%)	27

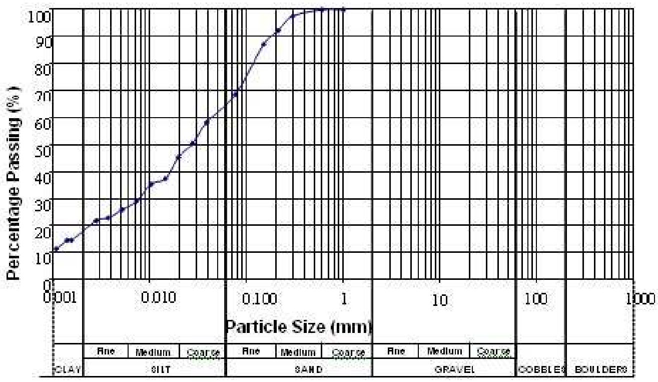

Fig. 3. Particle size distribution for Bengawan Solo fills: 36% Sand, 47% Silt, 17% Clay.

3.2 X-Ray Diffraction

Powdered x-ray diffraction tests were undertaken on this material to determine the clay and non-clay minerals present in the soil. Sample A refers to material sampled at 0.5m to 1.0m depth below the crest of the step of the embankment. Sample B was sampled at a depth of 1.0m to 1.5m. Fig. 4a presents the x-ray diffractograms of random powder samples using the total soil fraction. Fig. 4b presents the x-ray diffractograms of oriented samples in the <2 μm fraction under three different conditions: AO – obtained at room temperature, EG – after saturating with ethylene glycol and 550OC – after heating to 550oC

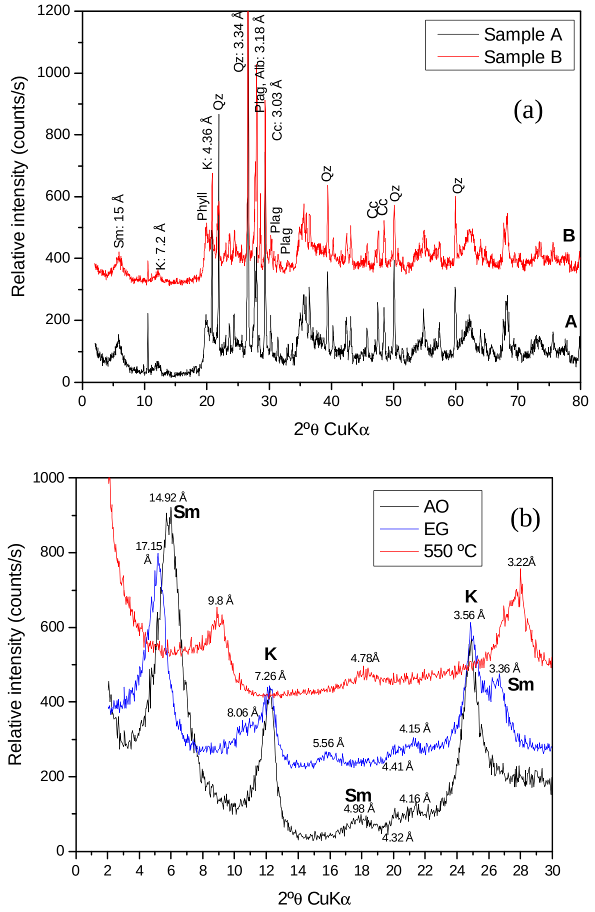

Fig. 4. XRD-patterns of (a) random powder samples (total fraction) and (b) oriented samples (< 2 µm fraction) for Sample B.

The random powder XRD identifies both the clay and non-clay minerals present in the soil. The significant clay minerals present are kaolinite and montmorillonite. The non-clay minerals present are quartz, feldspar (plagioclases) and calcite. The oriented XRD tests carried out on the clay fraction under different conditions highlight the clay minerals found Montmorillonite and Kaolinite

3.3 Soil Water Retention Curve

Fig. 5 presents the soil water retention curve for the Bengawan Solo fill material obtained using three different methods: filter paper method, pressure plate method and tensiometer. The filter pa-per method was carried out using Whatman No. 42 filter paper, where five specimens were pre-pared at a dry density of 1.2Mg/m3 and five different moisture contents. Two filter papers were sandwiched between 3 slices of soil for each specimen. The samples were left for 7 days to allow equilibrium to be reached. At a moisture content of 20%, the material at this density has a suction of almost 1000kPa. Increasing the moisture content to 36% reduces the matric suction to approximately 30kPa.

A tensiometer was also used to determine the matric suction of three specimens at 1.2 Mg/m3 dry density at three different moisture contents. The specimens were prepared in metal rings and sealed with double layered tin foil to prevent drying. The tensiometer was placed in direct contact with the top of the soil and was held in place using small weights with plasticine providing a seal around the probe, in a set-up similar to that used by Jotisankasa (2005). These results are in good agreement to those found using the filter paper method.

The pressure plate tests were carried out on samples with dry density of 1.18Mg/m^3, the samples were weighed on a daily basis to assess if equilibrium had been reached under the new applied air pressure. This could take up to 5 days to occur.

It is clear from Fig. 5 that the pressure plate method resulted in higher suctions than the filter paper method and tensiometer measurements for a given moisture content. This may be due to compression of water in the apparatus during application of the axis-translation technique as suggested by Navaneethan et al. (2005). However there are many other factors which may have influenced the suction measurements obtained in these tests, for example the use of an established filter paper calibration curve as proposed by Chandler et al. (1992) as opposed to performing an individual calibration.

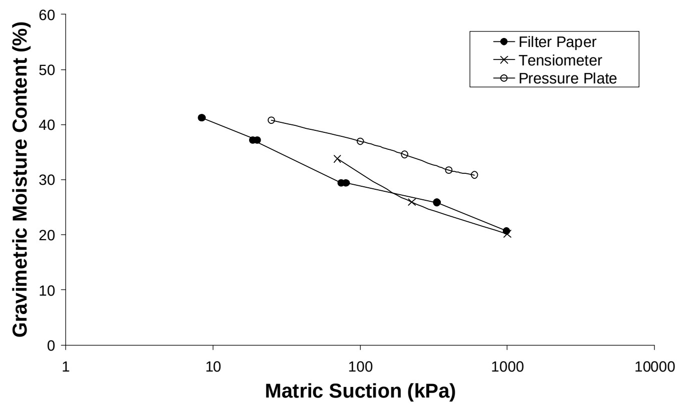

Fig. 5. Soil water retention curve.

3.4 Oedometer Tests

Oedometer tests were carried out on compacted specimens of particle size passing the 4.0mm sieve. Of particular interest was the behaviour of the soil at a low dry density and dry-of-optimum water content. Under these conditions the material was found to be collapsible.

Fig. 6 presents oedometer tests carried out under (a) dry-of-optimum (Series A); (b) wet-of-optimum (Series B); (c) prepared wet and dried to 20% (Series C); and (d) close to optimum (Series D) initial conditions. In Series A, specimens had an initial dry density of 1.16Mg/m3 and a moisture content between 18 and 19%. A fully saturated and fully unsaturated test is shown alongside two wetting paths where water was added at 63kPa and 127kPa respectively. It can be seen that after inundation the collapse curves follow closely the behaviour of the fully saturated curve. The final reading of settlement for all the collapse conditions presented here was taken 60mins after the addition of de-aired water.

Oedometer tests were further carried out wet-of-optimum (Series B) to highlight the importance of initial moisture content in producing collapse. These specimens were prepared at a dry density of 1.16 – 1.20Mg/m^3 and a moisture content close to 36%. Under these conditions tests were carried out on a specimen soaked at the beginning of the test, an unsoaked specimen and a specimen soaked at 63kPa. It is clear that under these wet conditions the addition of water does not result in collapse.

In Series C, the specimens were prepared at 36% moisture content and then dried to 20% moisture content; two different dry densities were tested: 1.26 and 1.38Mg/m^3. It is evident here that the specimen at 1.26Mg/m^3 on wetting at 127kPa resulted in significantly more collapse than the specimen of dry density 1.38Mg/m^3 wetted at the same vertical stress.

Series D, where the specimens had higher dry densities up to 1.46Mg/m^3 no collapse was ob-served under wetting at 127kPa, as expected. Furthermore at these densities the material was stiffer under the same range of vertical stresses applied to the other series, with the samples only beginning to approach their pre-consolidation stress at the end of the test.

Where collapse was observed the specimens were evaluated in terms of their collapse potential. The collapse potential was calculated from Eq. 1 (after Jennings & Knight 1957):

$$\text{Collapse Potential } = \frac{-\Delta e}{1+e_{unsoaked}} \times 100\% \qquad (1)$$

Where Δe is the decrease in void ratio of the specimen on wetting under the desired pressure (63kPa or 127kPa); $e_{unsoaked}$ is the void ratio of the unsoaked specimen at that pressure. Where swell potentials (positive values) are presented in Table 3, they were calculated as in Eq. 1, but with Δe equal to the increase in void ratio of the specimen on wetting. The collapse potential test as originally carried out by Jennings & Knight (1957) involved saturating the specimen after loading to 200kPa. Here much lower values of vertical stress were used: 63 and 127kPa; still significant collapse settlements were observed. Low pressures were chosen to identify if the collapse mechanism could be responsible for collapse under small loads such as those generated under the concrete protection slabs installed at the site (Fig. 2d).

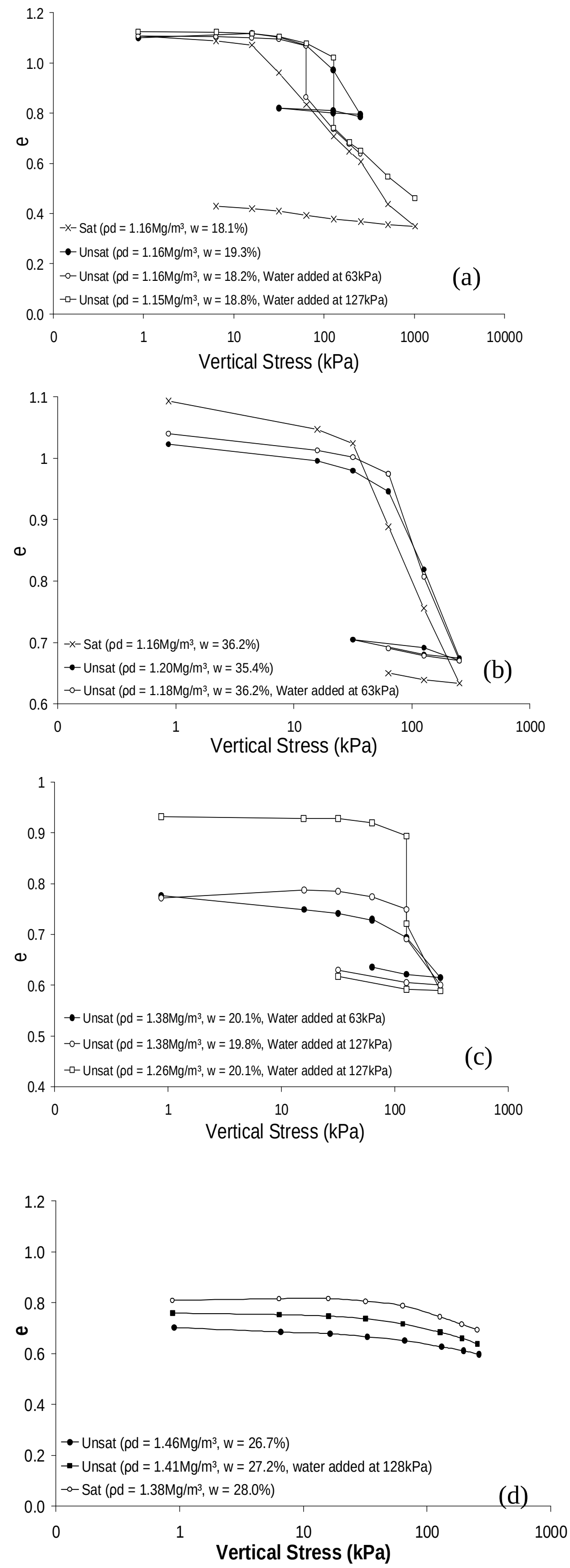

Fig. 5. Oedometer results: (a) dry of optimum, (b) wet of optimum, (c) prepared wet and then dried to 20% moisture content, (d) close to optimum conditions.

Table 2 presents a qualitative guide to understanding collapse potentials and the severity of the problem; this guide is primarily for use in relation to tropical residual soils, (Fookes 1990).

Table 2. Guidance for Collapse Potential (after Fookes 1990)

Collapse Potential (CP) (%)	Likely severity of problem
< 1	No Problem (NP)
1 – 5	Moderate Trouble (MT)
5 – 10	Trouble (T)
10 – 20	Severe Trouble (ST)
> 20	Very severe Trouble (VT)

Table 3. Collapse Potential and severity of collapse

Series	W (%)	ρ_d (Mg/m^3)	σ_v (kPa)	CP (%)	Severity (Fookes 1990)
A	18.2	1.16	63	-9.9	(T)
	18.8	1.15	127	-13.8	
B	36.2	1.18	63	0.0	(NP)
C	20.1	1.38	63	+0.13	Slight swelling
	19.8	1.38	127	-3.3	(MT)
	20.1	1.26	127	-9.1	(T)
D	27.2	1.41	127	0.0	(NP)

In Table 3 the results of Series A highlight the influence of the loading pressure at which saturation occurs; under the same initial conditions doubling the vertical stress increased the collapse potential by more than one third. This resulted in moving the severity from a Trouble scenario to a Severe Trouble scenario. Furthermore in Series C, an increase in loading pressure of saturation resulted in similar specimens changing from exhibiting slightly swelling behaviour (+0.13%) to exhibiting significant collapse behaviour (-3.3%). The overburden pressure is a key factor in producing a collapsible material.

From Series B it is clear that no collapse occurred on saturating a sample already wet-of-optimum. These results are in agreement with the suggestion by Lawton et al. (1989) that compacting wet-of-optimum can eliminate collapse behaviour. However this could not be implemented as a practical solution in Indonesia where flood embankment works can only be carried out during the dry season due to high river levels. Even if soil was compacted at a moisture content wet-of-optimum, the climate would ensure that the material dried quickly resulting in specimens not unlike those tested in Series C, where again collapse was observed.

From the filter paper retention curve (Fig. 5), a specimen at 1.2Mg/m^3 dry density and 20% moisture content has a matric suction value close to 1000kPa. For 36% moisture content at the same dry density, matric suction lies close to 30kPa. It is clear that suction is playing an important role in stabilising the structure of the unsaturated soil and for this reason at higher moisture con-tents (i.e. wet-of-optimum) where suction is already low, no collapse has been observed. More work is planned to include for suction monitored tests to be carried out in the oedometer to further verify the role of suction as the bonding force for this material.

The last two entries for Series C, in Table 3, highlight the influence of dry density on collapse potential. Both saturated at loading pressures of 127kPa, a decrease in dry density of 9% from 1.38Mg/m^3 (93% ρd_{max}) to 1.26Mg/m^3 (85% ρ_{dmax}) almost trebled the collapse potential deter-mined. The embankment under investigation was constructed at 80-85% optimum dry density; therefore the material as constructed is at a dry density suitable for collapse conditions. Further-more this result indicates that for this material a small reduction in dry density can have a significant impact on the collapse behaviour. For this reason good control of compaction on site during construction is of utmost importance.

The results identify that the Bengawan Solo fill material is a collapsible material at low dry densities, similar to those found in-situ and at dry-of-optimum moisture contents. Collapse potentials as high as 13.8% have been determined indicating that there is a severe problem regarding collapse of the soil under these conditions. The loading induced by engineering works at the site, combined with low dry densities, dry-of-optimum moisture contents and wetting from the river may have resulted in fulfilling the conditions required to produce collapse.

4. CONCLUSIONS

Some of the failures observed along the Bengawan Solo embankments have been presented here alongside the site investigation data highlighting the presence of low in-situ dry densities and low values of cohesion determined from shear vane tests. From determination of the soil properties the material has been classified as an inorganic silt of high compressibility. X-ray diffraction test carried out identify kaolinite and montmorillonite as the main clay minerals present and quartz, feldspar and calcite as the main non-clay minerals present.

Soil water retention curves were determined using three different methods: filter paper, tensiometer and pressure plate. The filter paper and tensiometer results were in good agreement, whereas the pressure plate results were found to given higher suctions for a given moisture content. This may be due to slight compression of water in the pressure plate apparatus. Even considering the slightly lower suction results from the filter paper retention curve, at 20% moisture content and a dry density of 1.2Mg/m^3 the material has a suction of 1000kPa and at 36% moisture content has a suction close to 30kPa. Thus moving from the initial conditions of Series A to Series B, the material has lost a stabilising force of approximately 970kPa, for this reason in Series B no collapse is observed. Suction acts as the binding agent in the unsaturated sample.

Oedometer results found that increasing the vertical pressure at which saturation occurred, resulted in higher collapse potentials. Increasing the initial moisture content of the specimen to wet-of-optimum, effectively eliminated collapse behaviour. Small decreases in dry density were found to significantly increase collapse potentials. This result highlights the importance of good compaction control during construction of embankments using this material. The collapse behaviour is thought to have been one of the main mechanisms resulting in failure of the gabion reinforced embankment and the differential settlements under the protection slabs at the site.

These preliminary results are part of an ongoing research being carried out at the University of Strathclyde on the Bengawan Solo fill material. Future work will include suction monitored and suction controlled experiments to further improve the understanding regarding the collapse behaviour of this material.

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