Behaviour of a silt used in flood embankment construction in Indonesia

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ABSTRACT: Oedometer tests were carried out on a silt used in flood embankment construction in Indonesia. Three test series were carried out under dry-of-optimum, wet-of-optimum and prepared wet and then dried, initial conditions. Where collapse was observed, the collapse potential for the specimen was evaluated and severity of collapse determined. This material has been sampled from embankments in East Java, Indonesia where there is a recurrent history of geotechnical failures. These preliminary results show the importance of good compaction control at the site and help to explain some failures observed at the site.

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. It has been reported that tropical unsaturated soils have been typically less studied than soils from temperate climates (Futai & Almeida 2005). Flood embankments are constructed of compacted fills and interchange between the unsaturated and saturated states depending on the water table, flood levels and also infiltrated rainfall and precipitation. 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. 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 has to be 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.

Figure 1 highlights some of the geotechnical problems encountered along the embankments of the Bengawan Solo River. Figure 1a 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. Figure 1b shows a global slip failure which occurred on the gabion reinforced section of the embankment. 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 Figure 1b 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, Figure 1c, 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 contents 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.

(a)

(b)

(c)

Figure 1. Failures along the Bengawan Solo Embankments: (a) erosion of natural embankments; (b) global failure of gabion reinforced embankments; (c) 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. Table 1 presents the material properties for the Bengawan Solo fill.

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)	1.44
Optimum moisture content (%)	27

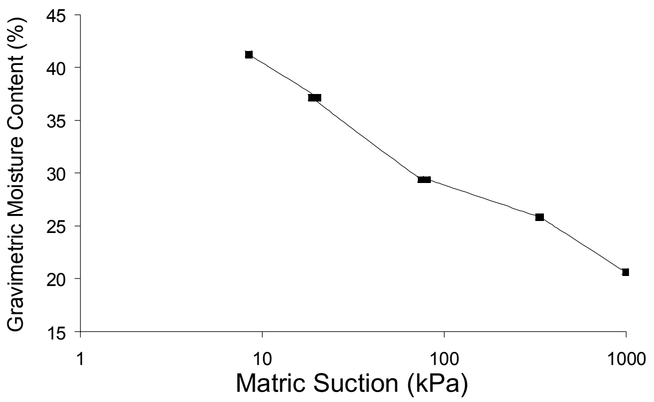
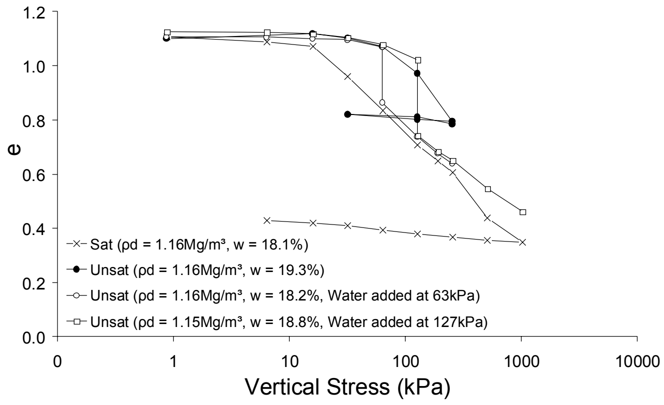


Figure 2. Soil water retention curve

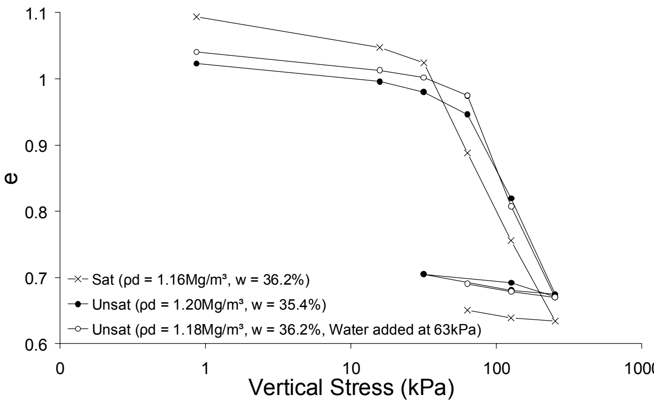
Figure 2 presents the soil water retention curve for the Bengawan Solo fill material obtained using the filter paper method. Specimens were prepared at a dry density of 1.2 Mg/m^3 and five different moisture contents. Whatman No.42 filter paper was used and the samples were left for 7 days to allow equilibrium to be reached. At a moisture content of 20%, the material at this density has a suction of almost 1000kPa.

3.2 *Oedometer Tests*

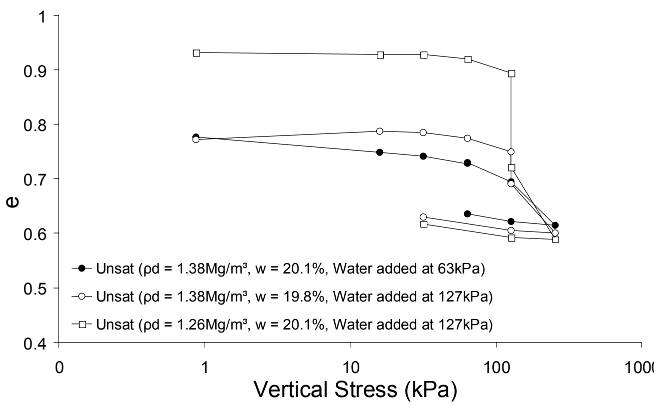
Oedometer tests were carried out on compacted specimens of particle size passing the 4.0mm sieve. Of particular interest was the behaviour of the soil at a low dry density and dry-of-optimum water content. Under these conditions the material was found to be collapsible.



(a)



(b)



(c)

Figure 3. Oedometer results: (a) dry of optimum, (b) wet of optimum, (c) prepared wet and then dried to 20% moisture content

Figure 3 presents oedometer tests carried out under (a) dry-of-optimum (Series A), (b) wet-of-optimum (Series B) and (c) prepared wet and dried to 20% (Series C) initial conditions. In Series A, specimens had an initial dry density of 1.16Mg/m^3 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 fact slight swelling was observed, Table 3.

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.

Where collapse was observed the specimens were evaluated in terms of their collapse potential. The collapse potential was calculated from Equation (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 Equation (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. 1c).

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 (%)	Likely severity of problem
< 1	No problem
1 – 5	Moderate trouble
5 – 10	Trouble
10 – 20	Severe trouble
> 20	Very severe trouble

Table 3. Collapse Potential and severity of collapse

Series	w (%)	ρ_d (Mg/m^3)	Vertical Stress (kPa)	Collapse Potential (%)	Severity (Fookes 1990)
A	18.2	1.16	63	-9.9	Trouble
	18.8	1.15	127	-13.8	Severe Trouble
B	36.2	1.18	63	+0.004	Slight swelling
C	20.1	1.38	63	+0.13	Slight swelling
	19.8	1.38	127	-3.3	Mod. Trouble
	20.1	1.26	127	-9.1	Trouble

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. However very slight swelling of negligible quantity occurred (Tab. 3). 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 retention curve (Fig. 2), 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 contents (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 in Table 3, Series C highlight the influence of dry density on collapse potential. Both saturated at loading pressures of 127kPa, a decrease in dry density of 8.5% from 1.38Mg/m^3 (96% ρd_{max}) to 1.26Mg/m^3 (88% ρd_{max}) almost trebled the collapse potential determined. 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. Furthermore 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

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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