

**THE EFFECT OF CLIMATE CHANGE ON INFRASTRUCTURE  
EMBANKMENTS: THE BIONICS PROJECT**

**A INFLUÊNCIA DAS EVOLUÇÕES CLIMÁTICAS EM ATERROS:  
PROJECTO BIONICS**

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**ABSTRACT**

An instrumented embankment has been built near Newcastle, UK as part of the BIONICS project, funded by the Engineering and Physical Sciences Research Council, to study the effects of the changing climate on infrastructure embankments. The BIONICS embankment is divided in six sections: two well compacted sections, two poorly compacted sections and two sections used for studying the effect of vegetation on soil properties. The embankment has an automated system allowing control of rainfall. Soil suction is monitored in both well and poorly compacted sections by using high-capacity tensiometers. Soil properties are representative of real embankments in the UK so that results from the BIONICS project can be directly used to infer information on the operational state of embankments throughout the country. Suctions profiles with depth are also recorded at regular time intervals, hence allowing observation of the seasonal evolution of soil suction.

**RESUMO**

Um aterro experimental foi construído perto de Newcastle, Reino Unido, como parte do projecto BIONICS, financiado pelo Engineering and Physical Sciences Research Council, para estudar os efeitos das mudanças climáticas em aterros. O aterro BIONICS está dividido em seis secções: duas bem compactadas, duas “mal” compactadas, sendo as restantes secções utilizadas para estudos relacionados com o efeito da vegetação nas propriedades do solo. No aterro será instalado um sistema automatizado que permite o controlo da pluviosidade. A sucção no solo é monitorizada nas secções bem e “mal” compactadas usando tensiómetros de alta capacidade. As propriedades do solo em estudo são representativas de aterros existentes em todo Reino Unido, sendo assim, com os resultados obtidos no projecto BIONICS poder-se-à inferir directamente informações à cerca do estado operacional de outros aterros por todo o país. Perfis de sucção em profundidade são também recolhidos em intervalos regulares, permitindo a observação sazonal da evolução da sucção do solo.

## 1. INTRODUCTION

Infrastructure embankments (i.e. earthdams, road embankments, railway embankments, flood defences) are likely to fail when pore water pressures increase significantly (and soil suction drops) following intense rainfall or flooding. With the predicted change in climate patterns, such failures will become more frequent with significant economic implications. The 4<sup>th</sup> Assessment Report of IPCC (IPCC, 2007) states: “Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21<sup>st</sup> century that would *very likely* be larger than those observed during the 20th century”. The likely effects of climate change can already be observed in the UK from the recent flood events that followed very large rainfalls and produced casualties as well as significant material losses (Carlisle in 2005 or Gloucestershire, Worcestershire and Yorkshire in 2007).

During the last decade several contributions have been made to the study of rainfall-induced landslides in natural soil deposits as well as infrastructure embankments (e.g. Corominas, 2000; Toll, 2001; Tsaparas et al, 2003; Glendinning et al, 2008). To further investigate such effects, an experimental instrumented embankment was built at the Nafferton farm, near Newcastle upon Tyne in the UK, as part of the BIONICS project (“Biological and Engineering Impacts of Climate Change on Slopes”), funded by the UK Engineering and Physical Sciences Research Council (EPSRC). The embankment is 90m long, 29m wide and 6m tall and is made of compacted sandy clay of medium plasticity with a top 0.5m drainage layer of coarse gravel. The embankment is divided in six different sections with the two central sections B and C (see Figure 1) well compacted according to modern construction standards, the two outer sections A and D poorly compacted as older Victorian embankments and the two outmost sections being used by biologists for studies on the interaction between vegetation and soil properties. The well compacted sections and the poorly compacted sections are representative of the compaction methods used for the construction of most infrastructure embankments throughout the UK.

The BIONICS embankment includes a climate control system composed of automated water sprinklers to simulate rainfall events of different intensity. The climate control system also includes a retractable cover placed on panels A and B, whose purpose is to shelter the embankment from rainfall and to limit the evapotranspiration caused by wind or radiation (Hughes et al., 2007). Two stations capable of measuring high values of soil suction have been installed in panels A (poorly compacted panel) and B (well compacted panel) of the embankment, about 2m away from the separation between the two panels (see Figure 1). Each measurement station consists of a probe locator, which is lowered in a borehole drilled on the top of the embankment about 1m from the south facing edge of the crest, and is fitted with five high capacity tensiometers for taking suction measurements at different depths. In particular the probe locator is made from a section of a PVC pipe through which are running five guide tubes used to locate the five tensiometers at depths of 0.5, 1.0, 1.5, 2.0 and 3.0 metres respectively (depths measured from the bottom of the superficial gravel drainage layer). The top of the probe locator was also sealed with foam and silicone to avoid any penetration of water or other kind of material through it. Electrical cables from each high capacity tensiometer run through the guide tubes inside the probe locator and are connected to a logging unit sited on the embankment crest. Such logging unit is in turn connected to a personal computer, hosted in a nearby hut, which reads the suction data and transmits them by means of an internet broadband connection. With this set up it is possible to obtain remotely real time records of the suction profile with depth as well as its seasonal variation.

## 2. BIONICS EMBANKMENT

The soil used for the construction of the BIONICS embankment is a sandy clay of medium plasticity presenting the following Atterberg limits: LL 42%, PL 23% and PI 19

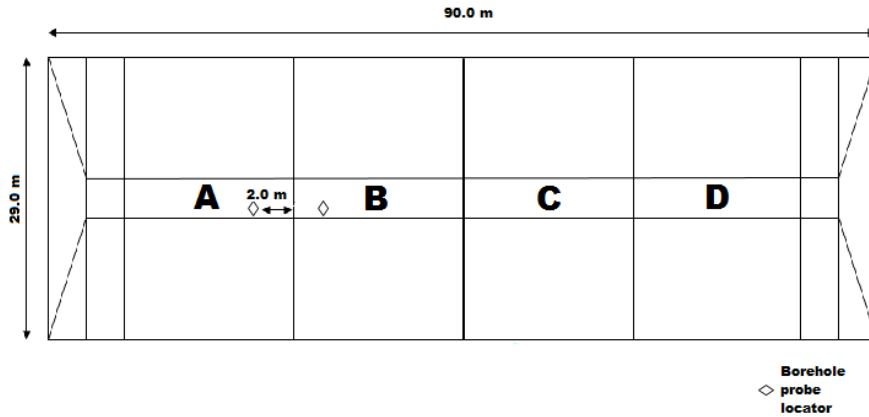


Figure 1 - Plan view of BIONICS embankment and borehole probe locators (after Glendinning et al, 2006).

Table 1 summarizes the average values of some of the soil properties measured from core cutters during construction of both the well compacted sections (panels B and C) and the poorly compacted sections (panels A and D). Inspection of Table 1 indicates that, as anticipated, the well compacted panels present higher density values and a smaller volume of air voids. Nevertheless the differences between the densities obtained from the two compaction methods are relatively small and less than expected prior to construction.

Table 1. Summary of core cutter measurements during construction (Hughes et al., 2007).

	Bulk Density (Mg/M <sup>3</sup> )	Water Content (%)	Dry Density (Mg/M <sup>3</sup> )	Air voids (%)	Degree of saturation (%)
Poorly compacted sections	1.93	20.7	1.6	6.0	85.3
Well compacted sections	2.01	20.1	1.7	3.2	91.4

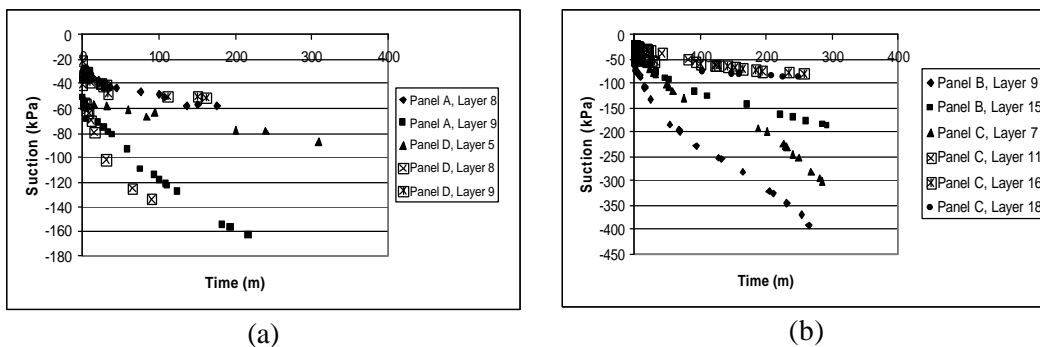


Figure 2. (a) Soil suctions recorded in samples taken from the “poorly” compacted sections of the embankment (Panels A and D), and (b) Soil suctions recorded in samples taken from the “well” compacted sections of the embankment (Panels C and D). After Hughes et al., 2007.

Additional tests showed that the well compacted panels are less permeable than the poorly compacted panels with permeability values of  $8.8 \times 10^{-11}$  m/s and  $1.6 \times 10^{-10}$  m/s, respectively. Preliminary suction measurements were also obtained during construction by using high capacity tensiometers on samples taken to the laboratory. Figure 2 shows the equalization curves of such suction measurements for samples taken at different elevations during the construction process (higher layer number indicates a shallower position with respect to the embankment crest). Inspection of Figure 2 indicates that the suction values measured during compaction of the well compacted panel are generally higher than those recorded in the poorly compacted panel.

### 3. THE EQUIPMENT AT THE BIONICS EMBANKMENT

In addition to the suction measurement stations and the climate control system, experimental facilities at the BIONICS site include inclinometers and extensometers to monitor settlements, piezometers to monitor the position of the water table and flushable tensiometers to measure low suctions up to 100 kPa. In the following part further details are given about the high suction measurement stations and the climate control system.

#### 3.1. High suctions measurement stations

The high capacity tensiometers used in the BIONICS embankment were jointly developed by Durham University and Wykeham Farrance Limited (Lourenço et al., 2006). The design of such a tensiometer is based on the same general principles of the suction probes firstly produced at Imperial College in London (Ridley and Burland, 1993) but the manufacturing process is entirely novel. The tensiometer measures soil suction (negative pore water pressures) through a high air entry value filter connected to a small water reservoir, which is in contact with a pressure transducer. When the high air entry value filter is placed in contact with the soil specimen, the pore water pressure equalizes with the water pressure inside the miniature reservoir (see Figure 3) causing a corresponding deflection of the transducer. The tensiometer developed by Durham University and Wykeham Farrance Limited can measure water pressures down to -2 MPa or even lower and, prior to the present work, it was mainly used in the laboratory. In order to use this tensiometer in the field a number of changes to the probe design had to be made. For example, the electrical cable that connects the probe to the logger was extended to 11m and protected by a stiff nylon tube (10m long with an internal diameter of 8 mm), which had the additional purpose of facilitating installation and removal of the tensiometer through the guide tubes running inside the probe locator; also the edges on the face of the tensiometer were smoothed for easy installation and removal. More information about the advantage and limitations associated to the use of such high capacity tensiometer in the field are provided in Mendes et al. (in press).

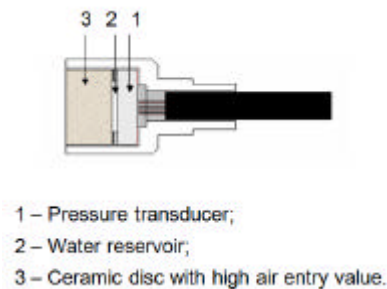


Figure 3 - Durham University - Wykeham Farrance high capacity tensiometer (after Lourenço et al. 2006).

The borehole probe locator has the only purpose of sustaining and protecting the guide tubes (used for the installation and removal of the tensiometers) inside it. In particular, it consists of a 3m long PVC tube with 70mm internal diameter containing the 5 guide tubes (made of reinforced flexible plastic) with 19 mm internal diameter. The extremities of the guide tubes were sealed inside holes drilled in the surface of the probe locator at depths where suction measurements had to be taken, i.e. 0.5m, 1m, 1.5m, 2m and 3m respectively. The guide tubes run up through the probe locator and emerged for a length of 0.5m to facilitate installation and removal of the tensiometers in the field. A small aluminium cylinder was fitted at the extremity of each guide tube to taper down the inner diameter from 19mm down to 14 mm (which is about the same as the external diameter of the tensiometer). This aluminium fitting helped to hold the tensiometer in place and prevented movement of soil into the guide tube. Such design enabled each tensiometer to be removed and inserted individually whenever necessary. With the exception of the measurement point at 3m that is placed on the bottom cross section of the probe locator with the corresponding guide tube running vertically, all other four measurement points are placed on the lateral surface of the probe locator with guide tubes bended at angle of about 45° with respect to the vertical. This is the maximum inclination compatible with the small internal diameter (70mm) of the probe locator and with the requirement of preserving ease of installation and removal of the tensiometers.

### **3.2. Newcastle University climate control system**

The Newcastle climate control system will be installed on the panels A and B on the south slope of the BIONICS embankment. The design consists on computer controlled roofing sections (infra-red reflective) that can be pulled over the two panels automatically when required (this provides a heating effect and reduces the heat loss when left overnight) and a system of rainfall sprinklers mounted on poles with upward-oriented nozzles creating a spatial and uniform rainfall at the ground surface. The rainfall input will be monitored by an automatic weather station installed at the south slope of the embankment, which will also monitor the wind speed, net radiation, temperature, relative humidity and atmospheric pressure, see also Hughes et al., 2007.

The proposed design is to ensure that the climate conditions are going to be the same conditions for expected future climate change.

## **4. FIELD RESULTS**

In this section some preliminary suction measurements recorded during the final period of 2007 are presented together with the daily rainfall over the same time. Tensiometers have been installed since April 2007, however the readings corresponding to the initial period of operation are not presented here. This is because, during the first few months after installation, it was noticed that the calibration relationship of the tensiometers slowly drifted with time (this was never a problem during use of tensiometers in the laboratory) and therefore needed periodic re-zeroing. In order to preserve accuracy of the measurements, the tensiometers are now being removed and their calibrations zeroed by submerging them in free water during periodic bi-weekly visits to the site (see Mendes et al., 2008). The dotted lines denoted by the bracketed numbers (1), (2), (3) and (4) in Figures 4 and 6 indicate the times of the site visits when such procedure took place.

The suction measurements recorded in the well compacted panel (panel B) are shown in Figure 4. Measurements appear to be rather consistent with time and to respond as expected to wet and dry periods. Inspection of the pore water pressure profiles along the vertical at different times (see Figure 5) indicates that it tends to decrease with depth attaining a value of about -30 kPa at

3m. Apart from the tensiometer installed at 1.5m (SS 3), which measured a significant jump at the end of October when it started to record positive values of pore water pressures, the tensiometers at other depths appear to measure relatively small variations of suction with time.

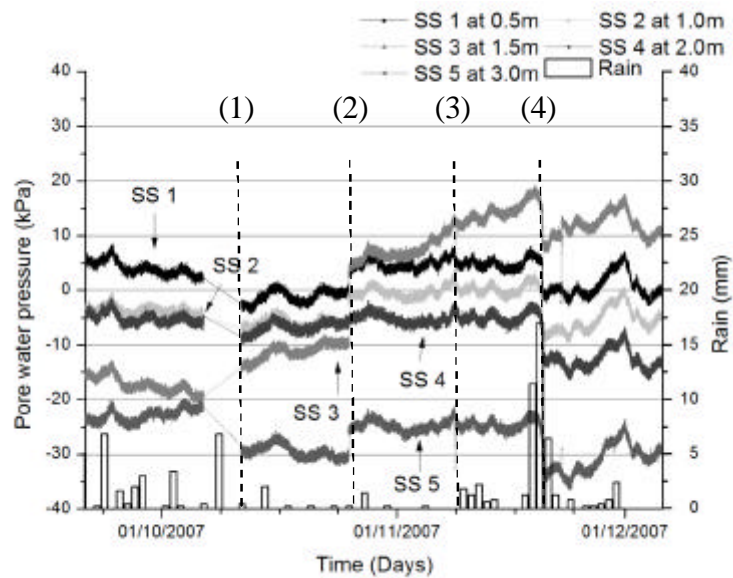


Figure 4 - Chronological variation of pore water pressure at different depths in the well compacted panel (shown together with daily rainfalls)

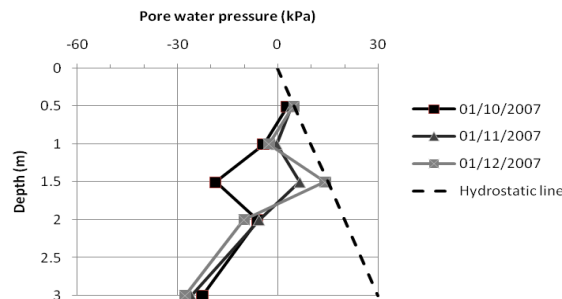


Figure 5 - Suction profiles with depth at different times in the well compacted panel.

Quite a different picture is shown for the poorly compacted panel (panel B) in Figure 6 compared to the data obtained in the well compacted panel. For example, one significant difference is that the tensiometers show a notably faster response and register larger changes of suctions during rainfall events with respect to the well compacted panel. In addition, unlike the well compacted panel, the response to rainfall events appears to be different in magnitude and direction at different depths.

Figure 7 shows the vertical profiles of pore water pressure recorded at different times in the poorly compacted panel. Inspection of Figure 7 indicates a different trend with depth as well as a wider variation of pore water pressures with time when compared with the well compacted panel. This might be explained by the fact that in the poorly compacted panel pore water

pressures respond more markedly to rainfall as a consequence of the larger permeability in comparison to the well compacted panel.

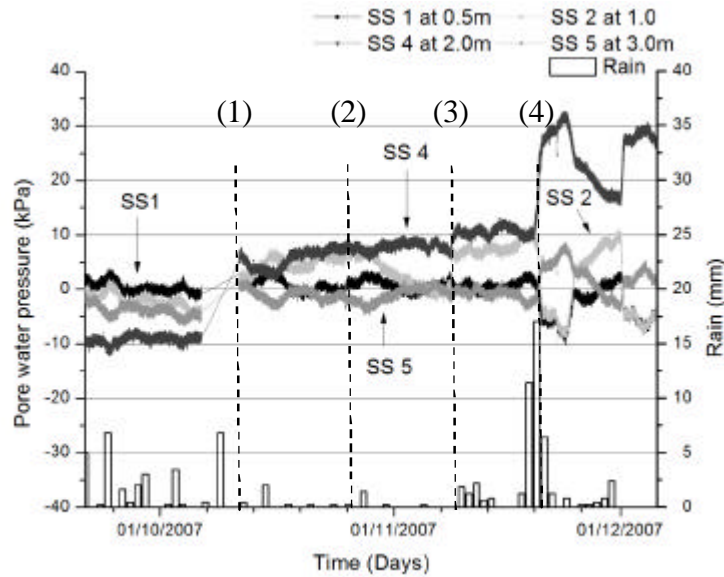


Figure 6 - Chronological variation of pore water pressure at different depths in the poorly compacted panel (shown together with daily rainfalls).

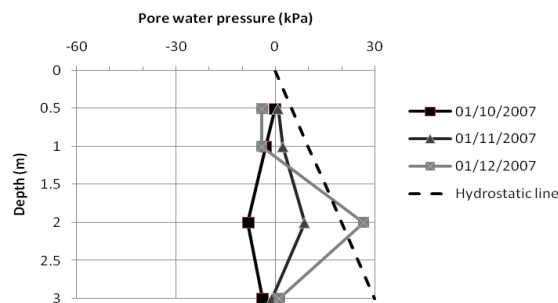


Figure 7 - Suction profiles with depth at different times in the poorly compacted panel.

## 5. CONCLUSIONS

An instrumented embankment has been built as part of the BIONICS project to study the effects of the changing climate on infrastructure embankments in the UK. The predicted change of climate is likely to jeopardise serviceability and stability of infrastructure embankments as has been demonstrated by the heavy rainfall events registered in the last decade across Britain.

The BIONICS embankment is divided in different sections constructed using different compaction procedures to reflect variability of properties of real embankments in the UK. The well compacted sections of the embankment show lower permeability (generating a slower response and smaller changes of pore water pressures during rainfall), higher density and higher values of suction both during and after construction with respect to the poorly compacted section.

A system for the field measurements of suction has been designed at Durham University and installed in both the well compacted and poorly compacted sections of the embankment. This system is currently yielding measurements of suction at different depths and at regular intervals of time. The readings of suction are taken by high capacity tensiometers connected to a logger and a computer, which transmits the data remotely via a broadband internet connection. One of the advantages of such system is that it allows easier removal of the tensiometers whenever necessary, for example, for re-saturation following cavitation or re-calibration.

## 6. ACKNOWLEDGEMENTS

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