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Non-intrusive Investigation and Slope Modelling of Compacted Soil in Heritage Geostructures

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Abstract

With changing climate slopes that have been stable for many years are becoming subject to failures. This is a serious problem for earthworks created before the advent of soil mechanics as we know it and suitable compaction equipment. Non-intrusive methods were used in order to produce a ground model to assess the slope stability of a heritage geostructure. This was then compared to a model derived from the limited intrusive investigation that could be undertaken, and the predicted change in groundwater regime added. The results are comparable and suggest that non-intrusive methods may be safe and suitable for difficult to access slopes where traditional methods may be deemed too destructive due to the significance of the feature or its potential instability.

Keywords: Slope Stability, Non-Intrusive.

1. Introduction

Whether Victorian railway embankments or Motte and Bailey castles there is a long history of earthworks in the UK. Many of these geostructures were constructed long before any standards, code of practice or even suitable compaction equipment were available. As climatic patterns become more erratic, with increased rainfall, flooding and extensive drought, it is important to understand how these changes may affect the stability of such geostructures, from the onset of cracking, water ingress, local slope failure and washouts. This study aims to develop a non-invasive approach to evaluate the current and future performance of these geostructures, helping to identify future instabilities that can then be rectified before they lead to failure, and assessing the importance of vegetation in preventing slope failure.

2. Background Information

2.1 Site History and Setting

The historic geostructure that this study will focus on is Baile Hill in York. This originally consisted of a Motte, a larger area of land surrounded by a ditch, and Bailey, the Baile Hill mound of interest. A small ditch was also likely present at the foot of the Baile.

The site is currently a steep vegetated mound present to the south of Cromwell Road and the east of Baile Hill Terrace, roughly centred around 460266E, 451274N. Neither the Motte nor the ditch at the base of the hill are still present.

Baile Hill is viewed as one of two castles constructed by William the Conqueror in 1069. It is believed that the castle was destroyed and rebuilt by 1070. The encircling ditch at the base of the hill, which is no longer visible, is considered to have been 21.00m wide and 12.00m deep based on excavations undertaken during the 1960s (Addyman, 1968). It is speculated by Addyman and Priestley (1977) that the ditch is filled from material washed from off the Baile Hill however it may have been filled in over time to allow the further expansion of the town of York.

An air raid shelter was constructed within Baile Hill on the western side between 1939 and 1945 with capacity for 251 people (https://her.york.gov.uk/Monument/MYO5236). However this may be present slightly to the south of Baile Hill against the wall, as anecdotal evidence puts it across from Kyme Street where a small gap is present in the knee high stone wall surrounding the monument. Its presence is not immediately obvious from historical mapping.

The topography of Baile Hill as seen today has been significantly altered over time but is likely to have been unchanged since the 1950s based on open source historical mapping. The ground conditions are only likely to have been significantly altered in the vicinity of the air raid shelter.

From historical sources it does not appear that significant failures have previously been recorded at the site. However, buttresses were noted on the outside of the wall close to Baile Hill which are not obviously present on historical maps of the walls. These buttresses were not noted elsewhere along the wall in this area, suggesting that there has been some historic movement, and attempts to rectify this, in the vicinity of Baile Hill.

2.2 Site Reconnaissance

A walkover survey was undertaken on the 26th April 2022.

The site was accessed via a small metal gate off the town walls adjacent to the southeast of the hill.

Inspection of the wall did not identify any significant cracks in the wall where it runs across Baile Hill but did identify that there were buttresses against the outside of the wall suggesting historic movement. To the south of the Baile Hill, along Princes Lane, the city wall showed severe cracking in places.

The hill itself was roughly 10.00m above the road level and vegetated with several mature sycamore trees. Lower down the slope to the southwest the ground is grassed and maintained.

In line with CS 641 methodology of inspecting slopes there were no observed features and signs of severe instability such as back scarps, soil/toe bulges, soil slips, dislocated features, and signs of mass movement of the slope itself. However there were significant patches of bare ground with no vegetation and while some of these features are likely due to public use, some on steeper areas of the slope are potentially due to shallow slips of the soil or erosion. In several areas deep shrinkage cracks could be observed where the ground had desiccated. Several trees were noted as leaning, potentially caused by soil movement. No tension cracks were observed on the crest of the hill.

2.3 The Potential Effects of Climate Change

Climate change predictions show a worst case sea level rise of around 800mm for the east of the UK by 2080 (Howard et al., 2019). Further to this there is also predicted to be a higher probability of extreme weather events, leading to average wave heights increasing by 2% each year (Woolf and Coll, 2006). Storm surges of between 2.00m to 3.00m already occur (Horsburgh and Lowe, 2013) and, while the River Ouse in York is not tidal, it is connected to the Humber Estuary and is tidally influenced up to Naburn, roughly 6km south of the centre of York, a rise in sea level may change this in the future.

It is also likely that the time between extreme events that would stress a slope would reduce, giving less chance for slopes to 'recover' from a previous event (Dijkstra and Dixon, 2010). For example drainage which may otherwise have been suitable for dealing with a sudden influx of water may not have long enough to drain away before the next influx.

Data on the water level has been taken from the GOV.UK website (https://check-for-flooding.service.gov.uk). Monitoring station 9387 present at York Castle Mills Sluices shows data for the River Foss, which joins the Ouse in the centre of York. The top of normal range is 7.80mAOD but the highest level monitored by the station was 9.28mAOD recorded on the 26th of December 2015 during a severe flood event.

Monitoring station 8081 present on the River Ouse at the Foss Barrier shows the top of normal range as 7.90mAOD with the highest recorded level of 10.20mAOD.

If 10.00mAOD is taken as the current worst-case scenario for the groundwater level for modelling purposes, to account for a projected water level rise of 0.80m and a worst case storm surge of 3.00m a future groundwater level of 14.00mAOD shall be modelled.

Increased rainfall may elevate the groundwater level within the hill itself which may have much more of an effect on its stability than an increase in the regional groundwater levels. Landslides are often associated with heavy rainfall events with 80mm to 100mm of rainfall over 24hours being clearly linked to slope failures (Guthrie et al, 2010).

With rainfall in the UK predicted not to increase much over the annual average but to become more condensed, with periods of drought and periods of intense rainfall this could have a much more deleterious effect on slope stability.

Modelling suggests that short duration extreme rainfall events are set to increase in frequency in the UK during the Spring, Autumn and Winter (Fowler and Ekström, 2009), although there is a great deal of variation across the UK, with the West coast showing a much higher predicted rainfall than the East coast.

Groundwater levels shall be modelled following the topography of the hill at a range of depth to help simulate a short lived groundwater regime within the hill during high rainfall events.

3. Field Work

An intrusive and non-intrusive investigation was undertaken of the mound in order to provide data on the ground conditions for modelling.

Through negotiations with Historic England a single Windowless Sample borehole was allowed on the top of the mound. Beneath the topsoil, made ground was encountered consisting of a silty SAND. Bone and mortar was encountered within this strata, with a very stone rich layer noted at 1.55-2.60mbgl. The Windowless Sampler struggled to progress the casing through this layer, suggesting that there may be a layer of cobbles of a diameter wider than that of the casing (101.6mm). Anthropogenic inclusions were no longer noted in what appeared to be potential natural strata by 2.60mbgl. This consisted of a desiccated slightly gravelly sandy CLAY. Due to the friable desiccated nature of the cohesive strata it was not possible to take shear vane readings.

No groundwater strikes were noted during the drilling of the borehole.

Standard Penetration Tests (SPT) were undertaken at 1.00m intervals. These provide an SPT 'N' value which can be modified to take into account the length of the rods, weight of the hammer and overburden pressure (N_{60}). Several correlations are possible between the SPT 'N' value and soil parameters such as the Angle of Internal Friction (ϕ) and Undrained Shear Strength (S_u) (BS 5930:2015+A1:2020). These shall be used to provide parameters for the modelling.

Samples of the clay were taken for Atterberg tests. The plasticity of these clay samples was low, even before taking into account the effect of grain sizes above 425µm which would further reduce the shrink/swell capacity of the clay. The Plasticity Index (IP) was then used to calculate the effective Angle of Shearing Resistance or Angle of Internal Friction (ϕ) for a fine-grained soil in line with BS 8004:2015+A1:2020.

The non-intrusive work consisted of a Ground Penetrating Radar Survey, Advanced Continuous Surface Wave and Resistivity Survey undertaking along the slope of the hill. This allowed the creation of a separate model of the soil strata and the estimation of the soil properties through the surface wave data.

As the Shear Wave Velocity (V_s) was dependent on the density of the soil, several parameters could be calculated from it along with inferences about where different layers of soil were present (Wair, DeJong and Shantz, 2015).

4. Parameters and Assumptions

In the following section the values used for each of the models shall be laid out and any assumptions highlighted.

4.1 Non-Intrusive

Based on the data collected from the non-intrusive investigations a ground model shall be outlined for testing and any gaps filled in with suitable conservative values.

The ERT seemed to suggest that the material in the hill had a higher resistivity, and this becomes a lower resistivity material at a depth of around 2.50mbgl. This is shown, albeit not so clearly, in the Ground Penetrating Radar, which provides some poor signal for the first 2.50m but then is completely lost. This shall be interpreted as a sandy material within the hill overlying a clay present at around 2.50mbgl under the hill (20.82mAOD). It is likely this clay is present at the surface at the foot of the hill.

The Continuous Surface Wave Testing provides differing information to this. The testing appears to show a change in strata at 14.00mAOD with a less clear change at between 21.00mAOD and 18.00mAOD. This could be the change between sandy and clayey strata noted in the ERT and GPR at around 21.00mAOD and the interface between clay material used to make the hill and the natural clay strata beneath it at 14.00mbgl.

There is potentially an infilled ditch at the foot of the hill, the area of high resistivity within the ERT at chainage 37 to 41 to a depth of around 2.50m. This shall be added to the model and the values of the Made Ground SAND used as it has a similar resistivity.

Table 1: Parameters used in stability modelling Non-intrusive.

Strata	Depth (m AOD)	Bulk Density (kN/m^3)	Saturated Density (kN/m^3)	Angle of Internal Friction (°)	Undrained Shear Strength (kPa)	Drained Shear Strength (kPa)
MG: SAND	20.82	16.48	20.00	34	0	0
MG: CLAY	14.00	16.48	20.00	32	80 + 25 per m)	0
CLAY	Base of model	20.00	22.00	27	40 + (10 per m depth)	0

4.2 Intrusive

The following parameters have been derived from field work and laboratory data. Assumptions based on field data and relevant published values will also be explained below. Samples taken from the cores retrieved were sent to Leeds University for geotechnical testing.

Due to limited data and ease of modelling, it shall be assumed that all soil layers are horizontal.

As no spring line or issues were noted during the site reconnaissance or during the intrusive works groundwater shall not be initially modelled but shall be added to simulate potential future levels.

The mound shall be separated into three soil horizons based on the findings of the borehole, discounting the thin topsoil layer.

Angle of Internal Friction for the granular strata shall be taken from SPT data.

As the cohesive strata was too friable for Shear Vanes to be undertaken the values calculated from the SPT shall be used. While these should be used with caution, observation of the soil onsite suggests that these high values may be representative. For the cohesive strata under drained conditions the Angle of Internal Friction as obtained from the Plasticity Index will be used. These values are deemed conservative due to the high proportion of granular material observed during logging.

Values for density for the soils have been based on the conservative densities presented in BS 8004:2015 in line with the SPT data obtained.

Table 2: Parameters used in stability modelling Intrusive.

Strata	Depth (m AOD)	Bulk Density (kN/m^3)	Saturated Density (kN/m^3)	Angle of Internal Friction (°)	Undrained Shear Strength (kPa)	Drained Shear Strength (kPa)
Medium dense brown slightly gravelly silty SAND	21.77	18.00	20.00	31	5	0
Medium dense light grey gravelly SAND	20.72	18.00	20.00	33	5	0
Firm consistency brown slightly sandy gravelly CLAY	Base of model	20.00	22.00	26	120	0

Drained Shear Strength shall be set to 0kPa for long term assessment of the slope. This is conservative but reasonable as a great many failures in clay strata are caused by loss of cohesion over time due to the release of negative pore pressures.

Although good practice when assessing a slope, no surcharge was used in these models.

5. Discussion of Results

5.1 Non-Intrusive

The results of modelling using parameters derived from the non-intrusive works are summarised in Table 3 below.

Table 3: Summary of slope stability results using Non-Intrusive Data.

Water Level (mOAD)	Undrained (Short Term)			Drained (Long Term)		
	Unity	EC7 DA1/1	EC7 DA1/2	Unity	EC7 DA1/1	EC7 DA1/2
0.00	1.282	1.282	1.052	1.282	1.282	1.045
5.00	1.282	1.282	1.052	1.282	1.282	1.045
10.00	1.282	1.282	1.052	1.282	1.282	1.045
14.00	1.282	1.282	1.052	1.282	1.282	1.044
Following topography at 5.00mbgl	1.282	1.282	1.052	1.282	1.282	1.043
Following topography at 4.00mbgl	1.282	1.282	1.052	1.282	1.282	1.039
Following topography at 3.00mbgl	1.282	1.282	1.052	1.282	1.282	1.037
Following topography at 2.00mbgl	1.282	1.282	1.052	1.263	1.263	1.017
Following topography at 1.00mbgl	1.282	1.282	1.052	1.021	1.021	0.817

From the modelling of the non-intrusive obtained parameters, it would appear that the slope is stable but only just. Even with the projected changes in the groundwater regime, it is only with groundwater set to 1.00m below the topography that values close to Unity are achieved.

However, there are signs of slope instability observed on the hill during the walk over. It may be that the results of the non-intrusive works are overly optimistic.

5.2 Intrusive

The results of modelling using parameters derived from the intrusive works are summarised in Table 4 below.

Table 4: Summary of slope stability results using Intrusive Data.

Water Level (mOAD)	Undrained (Short Term)			Drained (Long Term)		
	Unity	EC7 DA1/1	EC7 DA1/2	Unity	EC7 DA1/1	EC7 DA1/2
0.00	1.318	1.318	0.941	1.065	1.065	0.856
5.00	1.318	1.318	0.941	1.046	1.046	0.843
10.00	1.318	1.318	0.941	1.058	1.058	0.852
14.00	1.318	1.318	0.941	1.058	1.058	0.852
Following topography at 5.00mbgl	1.318	1.318	0.941	1.058	1.059	0.852
Following topography at 4.00mbgl	1.318	1.318	0.941	1.038	1.038	0.839
Following topography at 3.00mbgl	1.318	1.318	0.941	1.058	1.058	0.852
Following topography at 2.00mbgl	1.314	1.314	0.939	1.045	1.045	0.843
Following topography at 1.00mbgl	1.307	1.307	0.934	0.912	0.912	0.730

Initially running the model with the parameters derived from the site investigation data and the groundwater regime set to 0.00mAOD, the hill can be seen to be at the cusp of failure, with DA1/2 showing failure in both the short term and long term. DA1/1 is stable in both short and long term. Unity (Factor of Safety) shows 1.318 in the long term but reduces to an unsuitable 1.065 in the long term.

Almost all modelling shows the most likely failure to be shallow, with a deep-seated failure only occurring once the groundwater was 1.00m below the topography. This is in line with the findings of the site walkover, with small movement indicators and bent trees all over the hill but no large tension cracks at the top of the slope.

If these are the true properties and depths of the soil strata then the hill is being held together by something that we have not modelled, most likely the tree roots. From the observations during the intrusive investigation and the Atterberg Limits obtained from the samples retrieved the soils constituting the hill are very desiccated. This is most likely due to the action of vegetation in the area.

Raising the groundwater level in the surrounding area does not make much difference to the results until the groundwater level was modelled as a surface 1.00m below the topography of the hill. This situation is unlikely but, with sandy strata overlying clay and increased severe rainfall events forecast in the future, water may become perched within the sand overlying the clay.

6. Discussion

Non-intrusive methods suffer from the draw back relying on interpretation that, even with high levels of confidence, benefits from visual confirmation. Even the limited intrusive works helped to identify features within the non-intrusive data and isolate them from the background noise.

However, non-intrusive techniques allow the rapid covering of large areas providing information of ground conditions in areas that would otherwise be difficult to access with traditional intrusive investigation equipment. These methods avoid damage to the locations, avoid disturbance to the ground and as such can provide information on the in-situ soil without disturbance.

It was initially assumed that the GPR had struggled due to the composition of the hill being predominantly of clay. While this is true of the lower strata this ignores the fact that intrusive work encountered 2.50m of granular strata above the clay on the top of the hill. The poor performance of the Ground Penetrating Radar in this situation is not to say it will perform poorly in all situations. It would be best to use this method in areas where granular strata and a clearer change in density between the differing strata is likely.

The Electrical Resistivity Tomography provided a clear view of resistivity changes through the hill and was undertaken relatively quickly once the equipment was ready and working. However, there is ambiguity as to what causes the changes in resistance. On a much less vegetated site with a known groundwater regime the areas of high resistivity could be clearly linked with increased air voids. As it is, some areas of high resistivity could be the result of localised dewatering of the soil by vegetation. It would be interesting to undertake another survey with the same equipment and same line once all the trees had lost their leaves to help identify features caused by water demand of the vegetation. It would also be interesting to redo this section after a period of heavy rainfall to see if a short lived groundwater level appeared within the hill or perched within the sands above the clay.

The Continuous Surface Wave testing had provided the majority of the soil properties for non-intrusive slope model. This was fairly quick to undertake and has provided data that appears to correlate closely with that of the borehole undertaken. Once again it would have been interesting to undertake further intrusive works at the test locations in order to help recognise changes in strata.

Intrusive methods suffer from being destructive by nature, with even the most undisturbed sample not being representative of the soils true conditions in situ. The area investigated by such means is also small and unrepresentative of the soil across the site as a whole, a borehole undertaken only a few steps away could encounter vastly differing soil conditions. Increasing the density of investigation locations or excavating a larger area reduces the risk of variation in ground conditions within the site going un-noticed but inevitably causes more destruction and takes more time.

It would have been interesting to have obtained some undisturbed samples from the hill in order to undertake triaxial or permeability testing. The triaxial testing would have provided much more reliable values for the angle of internal friction and shear strength of the soils and the permeability would give a much better idea of how susceptible the hill would be to sudden influxes of water expected with the projected climate forecast.

In an ideal world the non-intrusive investigation would have been undertaken and its data assessed and used in order to help identify areas of interest for a targeted intrusive investigation. Resistivity anomalies, such as at the foot of the hill where there was a potential ditch, and part way up the hill where the archaeological excavation was undertaken could then have been assessed further and confirmed as to what they really are, and further boreholes could be undertaken to ensure the validity of the Shear Wave to soil parameter data.

7. Conclusions

Overall the models produced by the intrusive and the non-intrusive data are not too dissimilar, although further intrusive data should be gathered to give a true comparison.

It is clear that a slope stability assessment could be undertaken entirely through the use of non-intrusive data, although due to the level of uncertainty perhaps a larger factor of safety should be used in such a case.

The models produced by the intrusive data suggests the slope is at failure whereas the non-intrusive model shows the slope as just on the safe side. While not being a large difference in values it is still the difference between safe and unstable. Unfortunately, due to the limited nature of the intrusive works, we cannot assume that the model derived from the intrusive works is correct as it is based on one borehole.

The desiccated nature of the soils encountered during the investigation works and the fact that the hill is still standing while the intrusive data suggests it is close to failure all points to the influence and importance of vegetation on the hill.

The granular material on the top of the hill no doubt benefits from the roots providing an artificial cohesion to the soil. While the roots can also help maintain the negative pore pressure within clays, in hot weather desiccation cracks can form that will allow water to penetrate deeper and exert a force on a slope once the rain comes. In this case, with the clays being further down the hill, they are less likely to exert a lateral force that will negatively effect the slope.

Further work is recommended to assess the importance of vegetation in helping prevent slope failure and how this too may also be effected as the climate changes.

It is also recommended that further collaboration is needed between archaeologists and geologists in order to help prevent the collapse of historical geostructures. The complete lack of soil parameters or even reliable soil descriptions from intrusive archaeological work on the hill is a missed opportunity. The assistance of a geologist or geotechnical engineer, especially should earthworks be concerned, could provide a wealth of information that could help save these features and prevent damage or injury to those nearby.

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