Managed remediation of a large Victorian gravity quay wall using the observational method

Stabilisation d'un grand mur de quai de l'époque Victorienne gérée en utilisant la méthode observationnelle

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ABSTRACT: The paper describes on-going work to control the stability of a large gravity quay wall at a port on the western seaboard of the UK, which has had a history of instability dating back over several decades. In 1999 further ground movements of the wall were triggered by leakage from a fractured water main in the quayside behind the wall. This caused severe settlement damage to the quay and associated storage warehouses on the quayside. Monitoring of the affected area of the wall was established in early 2000, with additional ground investigations and instrumentation to supplement existing data. By the end of September 2000 the worst affected parts of the wall were moving outwards at a rate of 10mm/day. The movements were initially arrested by groundwater lowering. Subsequently additional remedial measures consisting of anchors and shear keys were designed and installed to provide physical restraint. The Owner wished to minimise capital expenditure and instead to use an observational approach (Peck 1969) and to respond to the information obtained. The work had therefore attained what was regarded as an acceptable steady state, with continued managed remediation to ensure that the wall's stability is maintained and the Owner can continue to use the berthing facilities.

RÉSUMÉ: Le document décrit les travaux en cours pour contrôler la stabilité d'un grand mur de quai dans un port de la côte ouest du Royaume-Uni, qui avait un historique d'instabilité datant de plusieurs décennies. En 1999, de nouveaux mouvements de terrain et du mur furent déclenchés par une fuite d'eau due à une rupture de tuyaux d'alimentation en eau du quai qui étaient derrière le mur. Ceci causa des dommages graves au quai et aux entrepôts de stockage sur le quai. La surveillance de la zone affectée du mur commença au début de 2000, avec addition d'instruments de mesure supplémentaires et investigations complémentaires du sol pour compléter les données existantes. À la fin de Septembre 2000, les zones les plus touchées du mur se déplaçaient vers l'extérieur à une vitesse de 10mm/jour. Les mouvements furent arrêtés par l'abaissement des eaux souterraines. Par la suite d'autres mesures correctives constituées de tirants d'ancrage et de piles pour éviter les glissements furent conçues et installées pour assurer la contention physique du mur. Le propriétaire souhaitait minimiser l'investissement initial et préférait utiliser une approche observationnelle (Peck 1969) en réponse aux informations obtenues. Le mur était assez stable pour utiliser le quai en continuant l'application opportune des mesures correctives pour assurer la contention du mur, et le propriétaire peut continuer à utiliser les installations d'accostage.

KEYWORDS: gravity walls; long-term monitoring; long-term displacements; ground anchors; water pressures; effects of dewatering.

1 INTRODUCTION

A section of harbour wall at a port on the western seaboard of the UK has a history of instability dating back over more than thirty years. Measurements taken in the 1980s had indicated that the maximum total horizontal movement of the wall up to that date had been more than 400mm. In 1999 further ground movements of the wall were triggered by leakage from a fractured water main in the quayside behind the wall. This caused outward movements along a length of over 80 metres, and severe settlement damage to the quay and associated storage warehouses on the quayside.

The harbour works were constructed at the end of the 19th Century. The wall is a gravity structure of mass concrete and masonry with sandstone "plums". At its top, it is some 17 metres above the harbour bed level; it is about 2 metres wide at its crest, increasing to almost 9 metres at its base. There is a large tidal range at the site.

After the 1999 movements, monitoring of the affected area of the quay wall was established in early 2000, with additional ground investigations to supplement existing data and to confirm the wall dimensions and the ground/groundwater conditions behind the wall. Inclinometers and piezometers were also installed to monitor water levels and the wall behaviour. Survey lines were established perpendicular to the wall and extending back to stable reference markers remote from the wall, with intermediate reference points to measure lateral and vertical movements in the ground behind the wall.

By mid-2000 the monitoring data showed a deteriorating situation, with outward movements of the wall accelerating from an initial value of around 15 to 20mm per month to as much as 100mm/month, and increasing. By the end of September of that year the worst affected parts of the wall were moving outwards at a rate of 10mm/day, and measures were put in place to stabilise the wall immediately in the short term, together with further works to ensure the stability of the quay wall in the medium term.

This current paper describes these measures and the long term monitoring of the wall over the past decade.

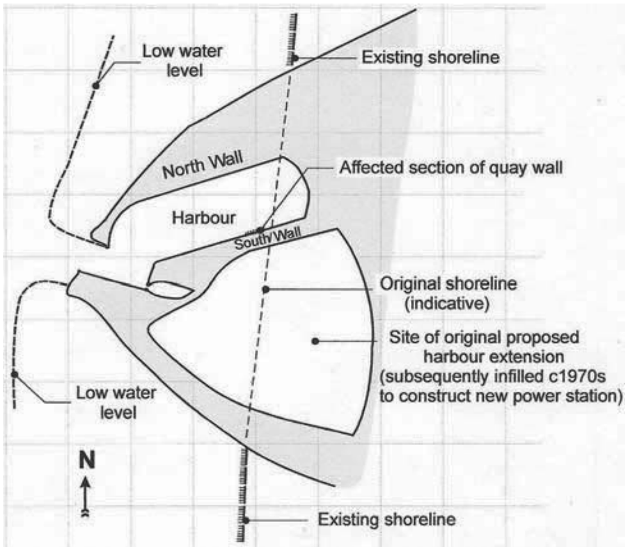

Figure 1. Outline plan of the site.

2 BRIEF HISTORY OF THE SITE

The harbour walls were constructed in the dry within a large embayment formed by advancing two curved embankments from the shore to meet at a central point, which would form the entrance to the harbour, as illustrated on Figure 1. This entrance point was closed by a temporary dam for the construction works and the site was drained by pumping. The harbour was then excavated in the dry.

A typical section through the quay wall is shown on Figure 2. The walls were constructed of mass concrete and, in the larger sections, large sandstone "plums" were incorporated into the concrete. The quay was intended for both passenger and livestock traffic. In view of the large tidal range provision was made for loading and off-loading at any state of the tide. This was achieved by constructing access-ways through the wall at two levels. These were connected to subways and stairways on the landward side of the wall. On the seaward side the quay wall was fronted by a heavy timber staging with continuous landings at the necessary levels to give access from the steamers into the subways.

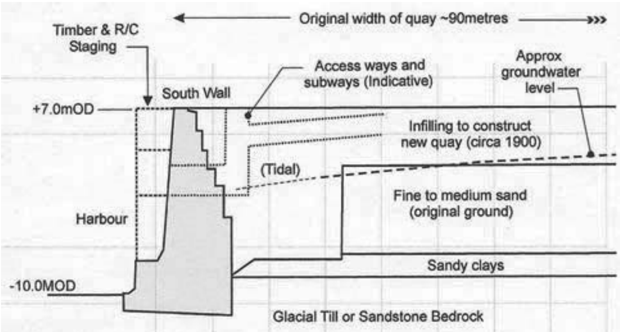

Figure 2. Typical cross-section through quay wall.

As illustrated on Figure 1, the affected quay, known as the 'South Quay' was constructed on the harbour side of a central spine embankment within the construction site. To the south of this, the remaining area was planned as a future extension to the harbour, but this extension was never constructed. In the 1970s this area was infilled and a large power station constructed on the site

In the early 1980s surface settlement was noted behind a 40m long section of the quay wall. This was repaired by infilling and relevelling to grade. Further repairs were undertaken in 1988, when a maximum settlement of 400mm was reported on the quay surface prior to reconstruction. Following these repair works the quay surface settled a further 30mm of settlement within a year, and the worst-affected area was reported as extending over an 85 metre length of the wall, although the effect was also discernible beyond this. Crane rails which had been relaid along the quayside in 1972 were found to have deviated by up to 100mm towards the harbour over a 100m length of the quay wall.

Detailed surveys taken in 1991 indicated that the South Quay was showing a distinct bulge of as much as 430mm towards the harbour, and the zone of movement extended for some 200m along the wall. Shortly after these measurements were taken, a break occurred in a water main some 13m behind the crest of the wall, due to the continuing outward displacement of the quay wall. At this time a remedial works solution using high capacity ground anchors was proposed, but not proceeded with.

In late 1999 a further major leak occurred from a fractured water main near the centre of the previous movements, causing accelerated wall movements and severe ground settlements beneath the quay itself. The next sections describe subsequent evaluation and remedial works following this particular incident.

3 GROUND INVESTIGATIONS AND OBSERVATIONS (2000-2001)

In early 2000 Applied Geotechnical Engineering was requested by the port owner to undertake investigations as to the cause of the movements and to advise on the measures required to stabilise the South Quay wall.

A targeted ground investigation was commissioned, to supplement information available from previous investigations undertaken in 1990/1992. In addition, inclinometers were installed at five locations along the crest of the affected length of wall and were continued through the base of the wall and any superficial soils into bedrock at depth. A further three inclinometers were installed behind the wall to monitor the behaviour of the retained soils. Water observation boreholes were also installed behind the quay wall to monitor groundwater conditions.

In addition a series of "traverse lines" was established perpendicular to the wall and extending back to stable ground well beyond any zone of influence of the wall movements. These were monitored by conventional surveying techniques to determine horizontal and vertical displacements.

3.1 Geology and Ground Conditions at the Site

The ground was raised behind the masonry quay walls using the material excavated to form the harbour. Beneath these surface construction materials, the South Quay is underlain by fine to medium grained sands of Quaternary age. In some places these are underlain by soft sandy silty clays. These materials rest upon either Glacial Till (typified as reddish brown, stony, clayey silts), or, more commonly, directly onto bedrock. At the western end of the quay, bedrock consists of sandstones with subordinate marls of Permo-Triassic age. Over the eastern end older sandstones and siltstones of Upper Carboniferous Namurian (Millstone Grit) age are present. The boundary between the two rock formations is formed by a large fault, trending in a NNW – SSE direction, which cuts at right angles across the line of the South Quay, slightly west of its central point, and close to the centre point of the historic movement of the wall. The fault zone was also identified during the construction of the power station to the south.

This fault zone is associated with heavy flows of groundwater under artesian or sub-artesian pressures. Before the power station was constructed a freshwater lake formed in the area of the old proposed harbour extension.

The investigations led to the conclusion that groundwater flows from this source to the south of the South Quay were the root cause of the wall instability, as described below.

3.2 Groundwater observations

It was soon apparent from the monitoring data that the movement of the wall was driven by the groundwater held behind it. The rate of drainage of the water below the wall was relatively slow, so that the difference in water levels between the front and the back of the wall was highest at low tide, as shown in Figure 3. At these points the wall would ratchet forward, and not quite recover its original location as the tide level rose. By inference, the effect was greatest at times of high tidal difference (Spring tides).

The water observation standpipes confirmed that close to the quay wall, water levels varied tidally between about +4m OD and +1.4mOD. Some fifty metres south of the face of the quay wall, water levels varied between +2.9 and +2.7m OD with the tide. At a distance of 100 metres groundwater levels were almost static, with very little discernible tidal variation, and were around +3.7m OD.

It was also noted that the salinity of the groundwater changed from south to north. In the south the groundwater was fresh or brackish. Close to the quay wall the salinity altered with the tide. At low tide it was brackish or fresh. At high tide, as seawater clearly flooded behind the wall, the groundwater became salty.

There was therefore a discernible hydraulic gradient from the power station site in the south, northwards towards the quay wall. It was also clear that the bulk of the groundwater was fresh water, flowing from the power station site towards the South Quay. In addition it was quite possible that concentrated groundwater flow was occurring in the fault zone in the vicinity of the harbour, although in the location of the South Quay the zone was buried beneath a cover of Glacial Till.

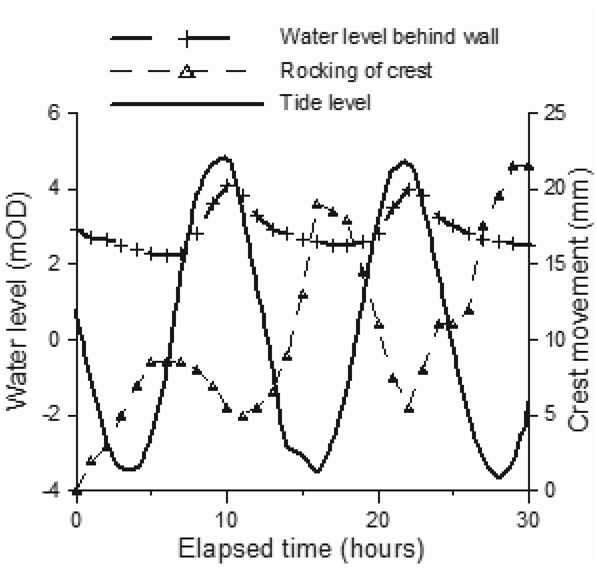

Figure 3 Water levels and crest movements, 13-14 Oct 2000.

The analyses showed that the high groundwater level behind the quay wall was the predominant driver of the instability and the observed wall movements.

3.3 Wall Movements (2000)

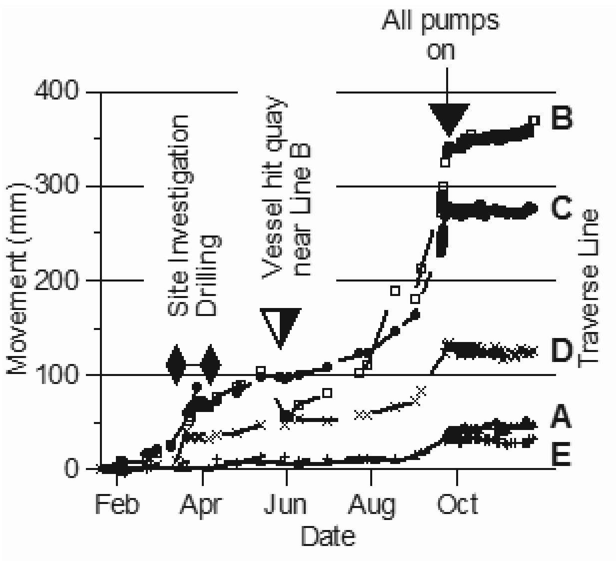

Figure 4. Crest movements during 2000.

The displacements of the quay wall measured at the traverse lines are illustrated on Figure 4. It can be seen that there was a noticeable effect upon outward wall displacements while the site investigation works were being undertaken in April 2000. Figure 4 also shows that the rate of outward movement also began to increase markedly in September of that year, and was accelerating. By September 2000 the worst affected area of the quay wall(Traverse Lines B and C on Figure 4) had recorded between 270 and 350mm of outward movement, relative to their values in January of that year. At this time the analysis, design and procurement of the remedial works was still being progressed, but, based upon the evidence of the increased wall movements during the investigation work, contingency plans had already been put in place to deal with such a situation. Eleven dewatering wells were installed in a line behind the quay wall at approximately 10m centres, to lower the ground water level behind the wall. At that time the wall was moving forward by more than 10mm per day at the worst affected part, and was rocking measurably with the tide. The pumps were started as soon as the wells were connected, over a three day period, the first three being commissioned on 17 October and the balance by 19 October 2000.

As soon as the first pumps were started, the wall movement virtually ceased, as can be seen from Figure 4. Measurements eight days later showed that the amplitude of the rocking motion was less than half its magnitude prior to pumping. With the wall stabilised, work on installing permanent drainage and ground anchors could begin. The effects of the dewatering upon the groundwater levels behind the wall are illustrated on Figure 5.

A feature of Figure 5 is that a distinct ‘plateau’ can be seen in the levels recorded for the water immediately behind the quay wall. The level of the retained water is drawn down to 0.0mOD by the pumping wells as the tide falls. It does not fall below this level, however, giving the step-like feature in the graph. The 0.0mOD level coincides with the invert level of the lower access-ways through the quay wall, which were open to the sea. When the tide was above 0.0m, on a falling tide, the retained water was clearly draining through these accessways, as well as being removed by the pumping wells. Once the tide fell below this level, then the pumping wells alone were removing the retained water, and, on the evidence of these readings, could only maintain the retained water at about the 0.0mOD level against the fresh water flowing from the landward side of the quay wall.

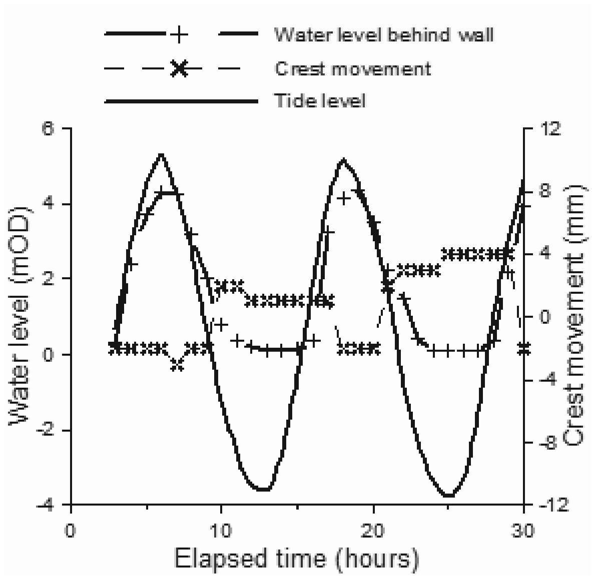

Figure 5. Water levels and crest movements 27-28 Oct 2000.

4 OUTLINE OF INTERIM REMEDIAL MEASURES (2001 – 2002)

It was recognised from the outset that the efficiency of the wells was likely to deteriorate in the medium term due to bio-fouling. Hence, additional measures were designed to provide physical restraint to the worst affected section of the wall. These consisted of seventeen 1050kN permanent rock anchors installed through the face of the wall at an inclination of 43^{o} to the vertical; twenty-four 525 or 626kN permanent anchors through the crest of the wall inclined to landward at 10^{o} to the vertical and approximately thirty near-vertical 63.5mm diameter shear keys into rock beneath the base of the wall.

In addition, a series of sub-horizontal drainage wells were installed through the quay wall at a level of +0.0m OD, to speed the drainage of the retained soils.

These works were completed in early 2002.

5 WALL BEHAVIOUR 2002 – 2012

The dewatering wells were shut off in April 2002 and the wall behaviour was monitored.

The response of the wall in terms of its outward movement as measured by the inclinometers and the traverse line surveys is illustrated in Figure 6.

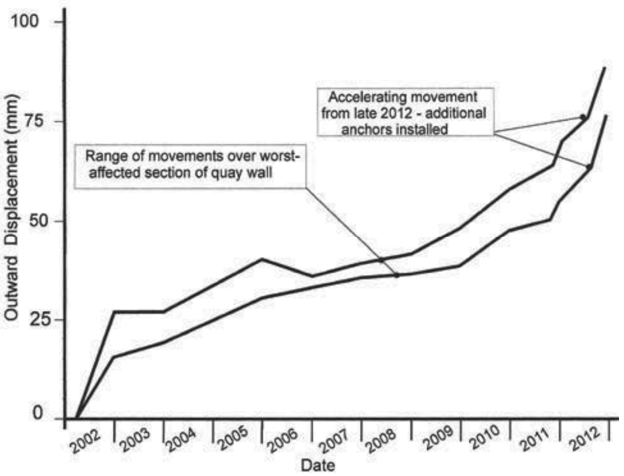

Figure 6. Wall displacements at crest level 2002 to 2012. (Toe displacements similar but generally smaller.)

Initial wall movements over the first 5-6 months were between 5 and 10mm at the crest and toe of the wall as the anchors took up further load. Load increases in the 43° anchors were typically between 50 and 200kN over this period.

By the end of 2002 the movements had stabilised at around 16 to 26mm at the crest, and 15 to 20mm at the toe. These data confirmed that the predominant mode of movement of the quay wall in the most active area was by sliding along a plane coincident with or close to the interface between the base of the wall and the underlying strata.

Over the next 3 years outward crest movements over the anchored section had increased to 30 to 40mm relative to the April 2002 readings and toe movements were between 35 and 40mm. Loads in the 43° anchors had increased by between 200 and 250kN. It had been planned to complete the main remediation works within this 3-year timeframe, but the monitoring works had demonstrated that movements were remaining controllable. The main works were put on hold, therefore and a watching brief was maintained on the wall. Based upon the previous readings, a movement criterion of 10mm/year had been adopted as a signal that further support works needed to be put in place.

By 2009 the loads in some 43° anchors were approaching or exceeding 1200kN – 15% above their design loads. Any anchors found to be in excess of this load level were being relaxed to avoid overstressing.

Outward wall movements over the anchored section generally continued at a rate of around 3 to 5mm per year.

By 2012, however, inclinometer and traverse line readings were indicating that outward wall movements were reaching 10 to 12mm per year, and the loads in the 43° anchors were increasing at an average of around 150 to 300kN per year. Additional interim measures were undertaken at the end of 2012, when a further six 1800kN capacity 43° anchors were installed through the face of the wall over the anchored section. The aim of these works is to reduce outward movements back to acceptable levels.

These additional limited-scope works are intended to allow the continued limited working of the quay, consistent with the current requirements of the Port. As demand rises or operational needs change at the Port, then full remediation works will be implemented to upgrade the South Quay facilities to meet this demand.

For reference, the data from Figures 4 and 6 have been combined on Figure 7 to illustrate the relative degrees of movement measured at the crest of the quay wall over the worst affected section from 2000 to the present day. The figure clearly shows the rapid, and probably catastrophic, accelerating rates of movement in 2000, before the dewatering was switched on, followed by the relatively slow but continuing movements over the next 9-10 years, but increasing latterly.

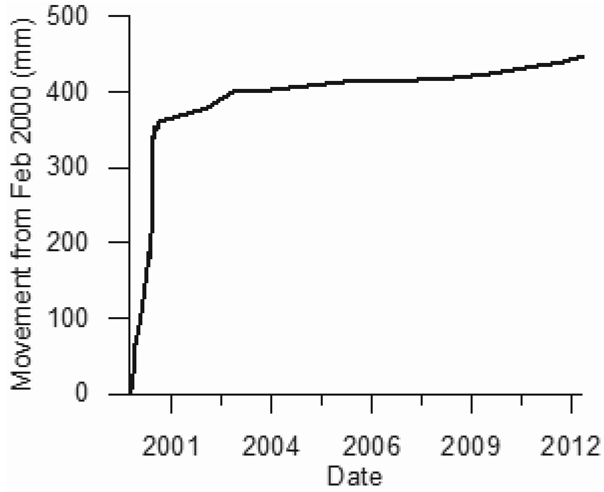

Figure 7 Wall crest movements between February 2000 and June 2012

6 SUMMARY AND CONCLUSIONS

The long-term monitoring of this 19th Century harbour wall over the last twelve years in particular, (but with records extending back over thirty years) has given a unique opportunity to gain an insight into the behaviour and relative ‘flexibility’ of such structures. The data gained from this work highlight the importance of monitoring such structures once they are perceived to be ‘at risk’, and the need to establish ‘trigger values’ related not just to overall movements but to rates of movement, and, in particular where rates of movement are seen to be accelerating over time.

7 ACKNOWLEDGEMENTS

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8 REFERENCE

Peck R. B. 1969. Avantages and limitations of the observational method in applied soil mechanics. *Géotechnique 19* (2), 171-187.