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Findings from a dewatering trial used to densify loosened natural soils

Résultats d' essais de rabattement de nappe phréatique utilisés pour densifier des sols naturels meubles

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ABSTRACT: This paper describes a use of dewatering as a means of re-densifying natural soils which have been disturbed by fluidisation. The Observational Method was adopted as the design approach prior to and throughout construction. The objectives of the project were to re-construct an existing foul sewer pumping station that had been damaged by ground settlement and to densify the ground to protect the new infrastructure and surrounding area against the effects of future movement. Densification of the loosened silty sand was carried out by temporarily lowering the groundwater using a combined ejector well and deep pumped well system. Monitoring of ground surface and subsurface movements, groundwater levels, pore water pressures, existing infrastructure and a nearby road and houses was undertaken. The initial ground loss event and ensuing damage which initiated the project is described, together with the ground conditions. Other options which were under consideration are presented and the reasoning behind the selection of densification by groundwater lowering using the Observational Method is set out. The findings from a trial of the groundwater lowering, monitoring and management system are presented.

RÉSUMÉ: Cet article décrit l'utilisation de rabattement de nappe phréatique comme moyen de redensifier des sols naturels perturbés par le phénomène de fluidisation. La méthode d'observation a été adoptée comme approche de conception avant et pendant la construction. Les objectifs du projet étaient de reconstruire une station de pompage d'égouts, endommagée par un tassement du sol, et de densifier le sol afin de protéger la nouvelle infrastructure et la zone environnante contre les effets des futurs mouvements. La densification du sable limoneux devenu meuble a été réalisée en abaissant de façon temporaire la nappe phréatique à l'aide d'un système de pompage combinant des éjecteurs ainsi que des puits profonds. Une surveillance des mouvements de la surface et du sous-sol, des niveaux des eaux souterraines, des pressions d'eau interstitielle, de l'infrastructure existante ainsi que la surveillance d'une route et de maisons environnantes a été entreprise. La perte de sol initiale et les dommages qui en ont résulté sont à l'origine du projet, ainsi que les conditions du sol. D'autres options examinées sont présentées et le raisonnement justifiant le choix de la densification par abaissement des eaux souterraines à l'aide de la méthode d'observation est exposé. Les résultats des essais du système d'abaissement, de surveillance et de gestion des eaux souterraines sont présentés.

Keywords: Dewatering; Densification; Loosened Soils; Monitoring; Pumping Station

1 INTRODUCTION

Long term ground settlements had been occurring in the vicinity of a Scottish Water (SW) pumping station in the Renfrew area of Glasgow, UK (Figure 1). These settlements were initiated by a collapse of the ground within the pumping station in January 2013. It is believed that this collapse may have been caused by a break in a deep foul sewer pipe which led to soil loss into the pipe and subsequent loss of volume and relative density, together with localised fluidisation of the saturated natural fine Sands that underlie the site.

Subsurface settlement then propagated upwards towards the surface throughout the sands and the Made Ground above. The depth of ground loss is presumed to be at or around the level of the foul sewer at approximately 6.5 m below ground level. The settlements damaged some of the buried and surface SW assets so that the pumping station was no longer operational.

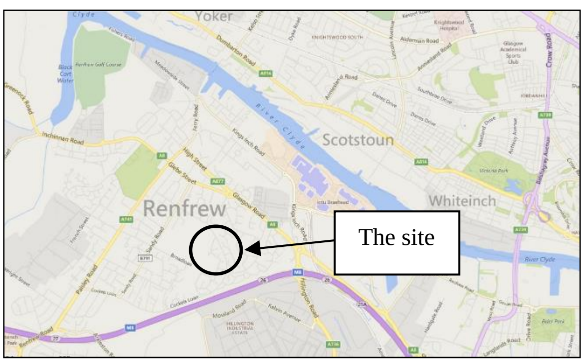

Figure 1. Site location plan

Morrison Construction Ltd (MCL) operated a temporary overpumping regime at the site. MCL were also commissioned by SW to construct a new pumping station at the site.

COWI (formerly known as Donaldson Associates Ltd), initially working for MCL, developed a ground consolidation / compaction scheme using groundwater lowering; this would temporarily lower the groundwater levels at the site over a period of several weeks. This reduction in groundwater pressures was designed to concentrate and accelerate any settlement potential from the collapse within a controlled environment into a concentrated event. It would also densify the ground which has been significantly loosened by the collapse, by increasing the effective stresses so that when the dewatering is switched off, the ground will remain in a slightly densified but stable state.

Advantage was to be taken by MCL of the dry soil conditions that would be created during this period to construct the deep civil engineering works of the replacement pumping station. However, it was recognised that dewatering could be relatively widespread and would result in some induced settlement below adjacent houses and other third party assets, and this had to be taken into account in the overall scheme and associated risk considerations.

As such an intensive monitoring system was designed then installed to measure surface and subsurface ground movements, groundwater levels and the position and tilt of houses and lamp posts. A framework for controlling the risk to these houses and assets was designed around this monitoring system so that the onset of damage could be identified and pre-planned interventions carried out if necessary, once certain pre-set settlement trigger values are exceeded. The key inputs into this assessment of potential damage and hence the design of these interventions were the permeability of the ground and the settlement response of the ground. Depending on the varying value of these inputs the dewatering was predicted to have the potential to have a wide range of impacts, from affecting only the two nearest houses (the ground is less permeable and the ground response is stiffer), to a larger number of houses up to 100 m distant (ground more permeable and less stiff).

COWI were subsequently employed by SW to review the instrumentation monitoring results during the implementation phase of the works, which commenced in January 2016, with advance works from September 2015. This paper focuses on the dewatering trial only carried out in July 2015 as part of the advance works and during the main works in March 2016 and associated monitoring works undertaken at the site. It presents relevant factual information, the interpretation of the findings, the significance of the results to the current design and makes recommendations of additions to the detailed design. The findings of the main works will be the subject of another publication due to the length limitation of this conference paper.

2 GROUND CONDITIONS

2.1 Geology

The ground level (Figure 2) on site is fairly uniform and generally varies between 7 and 7.5 mOD. The ground conditions were determined based on a number of ground investigations that have been undertaken at the site and the general ground sequence is as follows:

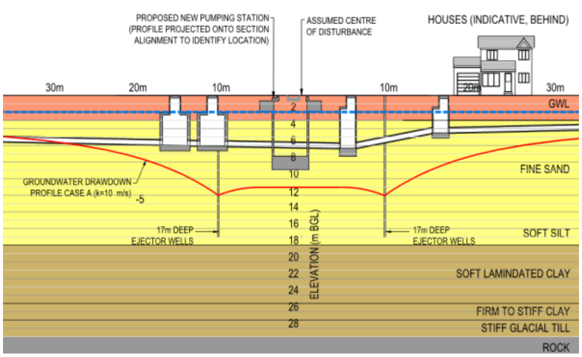

Figure 2. Ground model and groundwater profile

Made Ground associated with the construction of the pumping station and the previous use of the site (old Glasgow Airport) was present from ground level to a depth of around 2-3 m. Obstructions such as the remains of concrete slabs have been encountered within the Made Ground. Recent works around existing sewers also found that some pipelines were surrounded by gravel.

The Made Ground is underlain by Glaciomarine or Raised Tidal Flat deposits comprising intertidal and sub-tidal Silt, Clay and fine-grained Sand with lenses of Gravel to depths of up to 27 m below ground level. There is a clearly defined depositional sequence of silty Sand to a depth of 15 to 16 m, soft Silt to 19 m, another band of silty Sand to 21 m followed by soft laminated Clay to 25 m and firm to stiff Clay to around 27 m. Glacial till was encountered in boreholes at depths of between 27 and 29 m.

Groundwater was generally encountered at a depth of between 2 to 2.5 m below ground level, prior to any dewatering system being installed and operational.

2.2 Coeffcient of permeability k estimates

Three variable head tests were carried out in a cable precursion borehole (BH02) from a 2013 ground investigation. The layer in the borehole log is described as loose, slightly silty to very silty, fine to medium Sand. The coefficient of permeability k for different depths within BH02 are shown in Table 1.

Table 1. Coefficient of permeability k from borehole from variable head tests

Borehole	Depth [m bgl]	k [m/s]
	3.7-4.0	$1.62\ 10^{-6}$
BH02	6.7-7.0	$2.18\ 10^{-7}$
	13.7-14.2	$7.46\ 10^{-8}$

Mostap samples taken during the 2014 ground investigation indicated the predominant soil type within the depth of groundwater lowering is slightly to very silty Sand, locally slightly gravelly. Plots of the particle size distribution (PSD) tests carried out but not reproduced here show the relative uniformity of the material being medium to fine sand, with between 10% and 30% fines contents. Based on the PSD tests during the 2014 ground investigation, COWI assessed k based on two different methods; Hazen's rule (Hazen 1900) and Prugh's method (Prugh 1960). A range of k between 2.8 10^{-6} and 5.0 10^{-5} m/s was estimated based on Hazen's rule. A mean value of k=1.0 10^{-5} m/s was estimated based on Prough's method.

Constant head tests were also carried out on the Mostap samples from this 2014 ground investigation. The coefficient of permeability ranged from 5.7 10^{-6} m/s (located inside the dewatering ring and the zone of ground loss) to 4.4 10^{-5} m/s (located outside the dewatering ring zone).

3 ENGINEERING OPTIONS CONSIDERED

Four main options were considered in this review to address and if necessary remediate the unsatifactory the state of the soil. These were:

3.1 No intervention option

Allow the current settlements to continue over time and effect repairs to houses, roads and buried infrastructure respectively, using monitoring to control the risk. Repairs would be undertaken reactively and perhaps may be required repeatedly. The "no intervention" option was not developed further because the design remit was to develop a solution which has a high degree of certainty of success in managing the risk from ground movements.

3.2 Ground treatment

Treatments such as jet grouting and soil mixing were considered as part of this review. These treatments tend to create localised zones and columns of strengthened soil; i.e. a heterogenious material. The settlement risk might not be addressed effectively with such a solution because much of the soil, especially that in the locale of the adjacent houses, would remain untreated or poorly treated.

These treatments are relatively high energy systems and tend to disturb the soil during the installation process. Imparting such large energies into soil which might be at critical state (such as on this site) is ill-advised because the soil is likely to lose all effective stress and may liquefy temporarily, with uncontrollable effects over a certain area and serious consequences for services, roads and houses.

For these reasons this form of ground treatment was discounted.

3.3 Ground engineering to increase effective stress by dewatering

Dewatering would be used to increase the effective stress in the soil, thereby forcing the long term settlement to occur within the construction period.

3.4 Relocate the pumping station

The above solutions equally apply to the proposal to reconstruct the pumping station elsewhere since the settlement risk to the neighbouring properties would still need to be addressed.

4 ENGINEERING OPTION ADOPTED

Ground engineering to increase effective stress by dewatering was the prefered option. The objective is to force the long term settlements to take place within the construction period so that when the measures are removed the remaining settlement will be nil or negligible.

Groundwater lowering is a proven method of increasing effective stresses in the ground. Porewater pressure can be reduced by wells installed to depth below the zone of ground loss. The groundwater level would be drawn down by a predetermined depth and a steady state maintained until monitoring of subsurface, surface and structural monitoring confirmed that the rate of settlement had been brought under control. In effect the dewatering accelerates the settlement that might occur with no intervention, but this would be under more controlled conditions. Any damage could be mitigated by pre-works intervention and/or repaired in one, pre-planned visit on completion of the dewatering works.

The magnitude of the drawdown required is a function of the aim of increasing the vertical effective stress in the soils at and around the level of the foul sewer. There is little benefit in drawing the water down below the soils which have been loosened by the ground loss, and indeed the greater the drawdown the higher the risk is of causing damage to adjacent properties. The question to be answered is whether this level of drawdown will effect the changes in the soil which it is intended to do.

At the level of the foul sewer the increase in effective stress is 50 kPa, or an increase of more than 60 %. If the settlements induced by the drawdown are complete by the time the pump wells are switched off then the dewatering will have artificially increased the overconsolidation ratio from 1.0 to 1.7 at sewer level and proportionally in between.

Drawdown to below the level of the new pumping station construction is also beneficial to allow the new pumping station shaft to be constructed in dry conditions using the caisson method and the new foul pipes installed by simpler tunnelling methods than if water was present.

5 MONITORING

Monitoring instrumentation was installed in May 2015. A total of 19 piezometers were included as part of the monitoring instrumentation set up on site. The data were available and downloadable in real-time from a website platform. Manual dips of the piezometers were also carried out. The key instrumentation located inside the dewatering ring comprises instruments MWB0, MWC0, EJ11 and MW3.

Four Extensometers with 6 anchors each were installed in new boreholes to monitor subsurface movement throughout the thickness of the superficial deposits. The extensometer data was automated and available in real-time. Extensometers 01 and 02 are located within and on the perimeter of the dewatering ring respectively, whilst extensometers 03 and 04 are outside the dewatering ring.

Fifteen tiltmeters were installed on the external walls of houses to measure angular rotation in two planes on two faces of the buildings; the data was automated and available in real-time.

Nine reflective 3D targets, measuring x, y, and z positions were placed on the external walls of private houses; in addition, targets were installed on three of the lamp posts.

In excess of ninety near surface and precise levelling points were installed throughout the site to monitor the changes in elevations during the works. The precise levelling points comprised generally nails placed at surface on road, kerbs, external houses walls, manhole lids; whilst near surface points (nineteen in total) were installed using a metal plate placed below the base of concrete obstructions within the made ground (old broken concrete slab) and extended with a metallic rod to monitor movement below the obstructions, as there was concern that the presence of the concrete slab could mask the settlement occurring by a bridging action of the surfacing.

The frequency of the automated monitoring was generally set at 15 mins, although this was amended to minute readings for key phases such as the switch-on and off of the dewatering systems and recovery tests. The precise levelling and 3D target surveys were manual and were carried out daily to twice daily depending on site activities.

A laser survey was undertaken in July 2015 prior to the dewatering trial to provide a baseline prior to the works commencing. A repeat survey was carried out on completion of the construction of the pumping station; its purpose was to visualise changes in elevation and in position, such that this difference can be viewed and interrogated both qualitatively and quantitatively.

6 FIRST DEWATERING TRIAL

The dewatering trial consisted of a one day stepped test, a 3 day constant rate pump test and a recovery period.

6.1 Permeability from dewatering trial

On completion of the dewatering trial carried out in July 2015 (Figure 3) the original target drawdown level from 2 m bgl to 12 m bgl, had not been achieved. The ejectors (Figure 4) only managed to draw down the groundwater level by approximately 3.5 m inside the dewatering ring.

Further assessment of k from the dewatering trial was undertaken based on the data collated in three monitoring wells (MW1, MW2 and EJ16). This indicated a range of k of 8.5 10^{-6} m/s to 1.1 10^{-5} m/s.

An additional three falling head tests were carried out in August 2015 (MW1, MW2 and EJ16) to gain further confidence on the range of k. The values obtained ranged from 9.37 10^{-7} m/s to 1.29 10^{-5} m/s.

Based on all the available data gathered (both raw and analysed), it is considered that k of the ground lies between 2.0 10^{-6} m/s to 3.0 10^{-5} m/s. The coefficient of permeability k derived from the dewatering trial, at 1.1 10^{-5} m/s is considered to be the most likely value based on results from dewatering trial. Permeability should be considered a range rather than a single value, owing to the natural variability of the ground and further variability caused by the settlement event of January 2013.

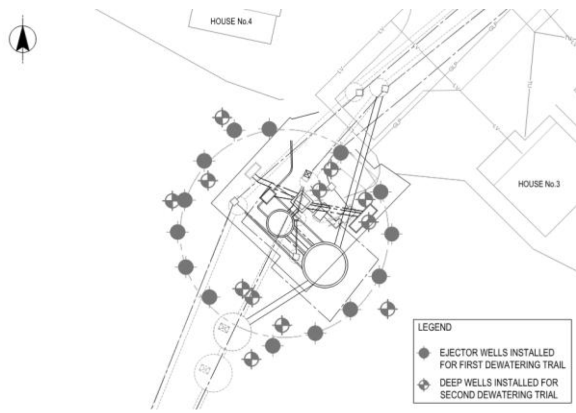

Figure 4. Plan view showing location of wells

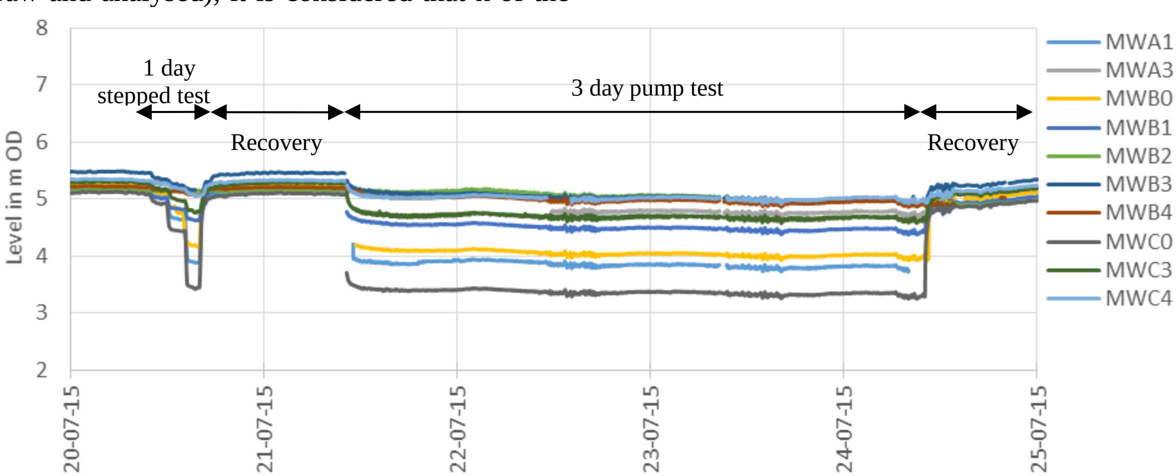

Figure 3 Drawdown achieved from first dewatering trial

6.2 Settlements

The monitoring data indicated that the installation of the ejector wells, drilling, developing and commissioning induced movements of up to 7 mm (EXT01). The commissioning of the wells generated almost immediate ground movements (1.8 mm EXT01, 1.2 mm EXT02, 0.4 mm EXT03 and 0.2 mm

EXT 04). Finally, the pump test also confirmed this reaction and that when the pumps were switched off, the settlement profile plateaued (Figure 5).

The ground appears to have responded as expected, indicating that the dewatering has started to densify the ground. Ground movements outside the dewatering ring were lower than inside and this is also as expected.

The main dewatering works commenced on site on 13 January 2016 with a target drawdown of 10 m. Following the initial depressurisation period on site in early January 2016, it became apparent that the original system of ejector wells was not capable of achieving its target.

The poor performance of ejector wells was put down to unidentified source(s) of groundwater recharge, such that the groundwater model is a quasi/pseudo aquifer with local feed. Two scenarios were considered for this recharge; (i) background groundwater recharge from natural gravel connected to a localised infill area (undertaken most likely after historic loss of ground event) or (ii) leakage from disturbed or damaged pipe beddings, or a combination of both.

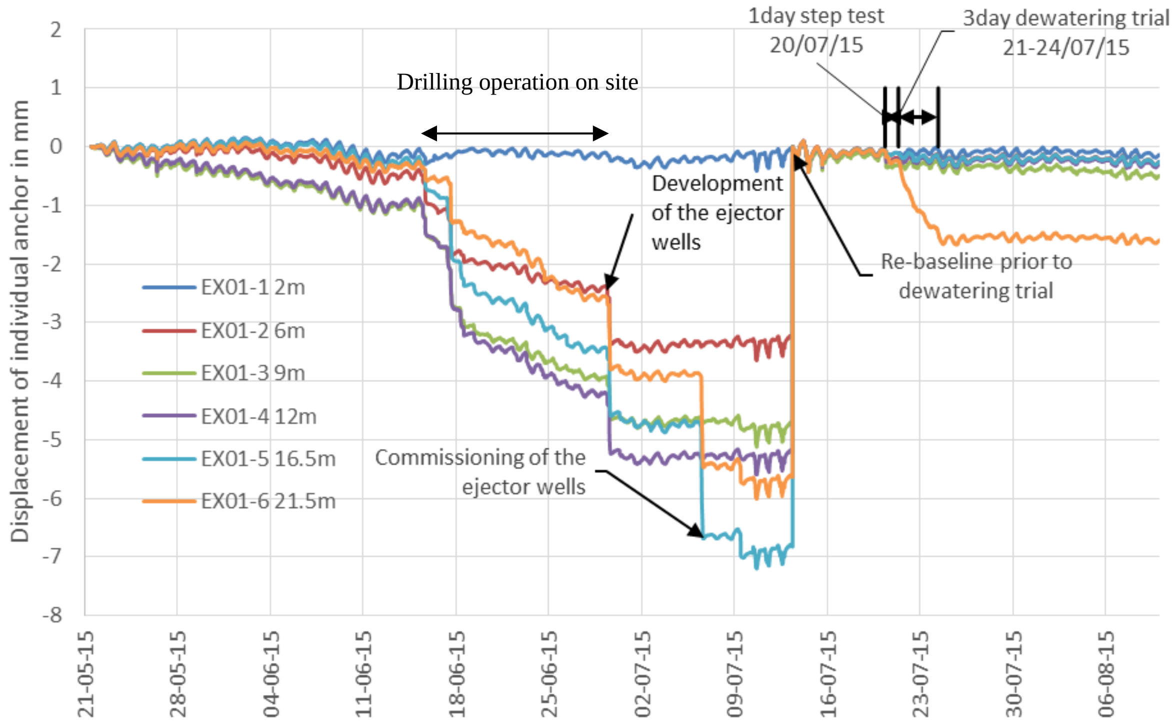

Figure 5 Settlements at the extensometer EXT01 within the dewatering ring due to first dewatering trial

7 SECOND DEWATERING TRIAL

The depressurisation strategy was modified to account for this additional source(s) of groundwater. The primary goal was to increase flexibility in the dewatering system in order to cope with apparent variations in ground conditions. To assist in achieving a suitable solution, the target design drawdown level was amended as follows:

Groundwater level to reach 5.5 m drawdown or lower within the dewatering ring area footprint to achieve ground densification;

Groundwater level to reach 8.0 m drawdown or lower below the footprint of the new pumping station shaft (i.e. 1 m below underside of shaft concrete plug to facilitate construction).

A supplementary dewatering system comprising eleven vacuum assisted deep wells with submersible pumps (Figure 4) were subsequently installed during March 2016. The existing ejector system was restarted on the 29th of March. The supplementary submersible pumps system was fully operational from the 30th March, with vacuum assisted pumping on the supplementary wells added on the 31st March 2016.

With the additional dewatering system in operation, the drawdown achieved approximately 6.4 to 8.5 m and thus met the revised target inside the dewatering circle for the purpose of ground densification.

8 CONCLUSIONS

The dewatering works confirmed that the ground has broadly responded quickly and as expected in terms of settlements and changes in groundwater levels. Also the current design philosophy remains valid but with a revised dewatering target.

9 ACKNOWLEDGEMENTS

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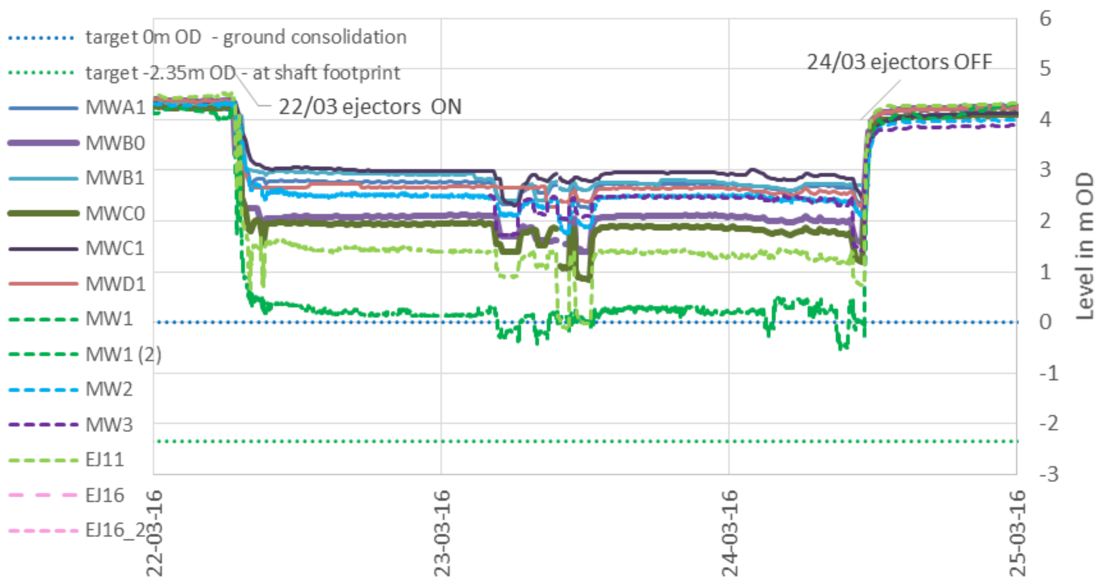

Figure 6 Drawdown achieved from second dewatering trial

10 REFERENCES

Cashman, P.M., Preene M. 2013. *Groundwater lowering in construction*, CRC Press, Boca Raton.

Powers, J.P., Corwin, A.B., Schmall, P.C., Kaeck, W.E. 2007. *Construction dewatering and groundwater control: New methods and applications*, John Wiley & Sons Inc, New Jersey.

Hazen, A. 1900. *The filtration of public Water Supplies*, Wiley, New York.

Prugh, B.J. 1960. New tools and techniques for dewatering, *Journal of the construction division, Proceedings of the American society of civil engineers* **86**, 11–25