Engineering Geology and Tunnelling in the Limmo Peninsula, East London

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Abstract

The Limmo Peninsula site has some of the most complex geology of London's Crossrail project and was the launching point for four Tunnel Boring Machines (TBMs) to enable construction of Crossrail's eastern running tunnels. It is located in East London, approximately 2 km east of the Canary Wharf business district, adjacent to the River Lea. It consists of a ventilation shaft, an auxiliary shaft, two sprayed concrete lining (SCL) tunnels interconnecting the shafts and four SCL adits for assisting in the launching of the TBMs. As part of the design requirements, some geological formations had to be depressurized from surface wells. The site is geologically complex: it is in the vicinity of a drift filled hollow and it is located within the area of influence of several tectonic features. A geological ground model developed from important new information obtained during the design stage ground investigations and from direct observations conducted during construction stages reveals an inverted transtensional flower structure (i.e. it is now a transpressional restraining bend). Of special interest are the unusually low values of undrained shear strength of the London Clay associated with the tectonic setting.

Introduction

Crossrail links east and west of London with a new railway (Black *et al.* 2014), which crosses the Limmo Peninsula , East London. As anticipated, a range of features consistent with faulting were encountered during construction at the Limmo Shafts site on the east bank of the River Lea, north of the Lower Lea Crossing Bridge (Figure 1). The site is in the floodplains of the River Thames and the River Lea and therefore the topography is flat and low-lying; the ground elevation is approximately +7 m AOD (+107 m ATD).

FIGURE 1

The principal structures at the site are the main shaft, the auxiliary shaft and the sprayed concrete lining (SCL) tunnels. The Main Shaft is 44·3 m deep and 30 m in diameter. The stability of the excavation was provided by a diaphragm wall with a toe level 55 m below ground level. The Auxiliary Shaft is 39 m deep with an internal diameter of 27 m. The initial 17 m was constructed using sheet piles, with sprayed concrete used for the remainder of the shaft. The SCL tunnels provided twin connections for the shafts and also for back and launch adits. They have a tear drop shape that is 8·65 m vertically and 7·98 m horizontally.

The presence of faults and drift filled hollows (Figure 1) at the confluence of the River Lea and the River Thames is well documented (Berry 1979, Hutchinson 1980, Banks *et al*. 2015) and led to challenging design and construction conditions. Faults cause a range of geological and hydrogeological hazards, by creating either low-permeability boundaries or high-permeability pathways that affect predicted groundwater behaviour, and by fracturing and damaging the ground, leading to face instability, large volume losses and settlements when encountered during tunnelling and bulk excavations.

1 Geological Context

The site is located in a part of the London Basin long known to be structurally complex (Howland 1991, de Freitas 2009, Royse *et al.* 2012) but only recently recognised as being close to the line of a major basement wrench fault (Ghail *et al.* 2015) that has been reactivated by ongoing inversion of the

London Basin. Mason *et al*. (2015) measured a sinistral slip rate of ~1·5 mm a^{-1} over recent decades and it is likely that this movement has reactivated other basement normal faults, causing reverse offsets of the London Clay and Lambeth Group of up to ~10 m (Ghail *et al.* 2014).

The Limmo Peninsula also contains several drift filled hollows, coincident with anomalous rock head on the upper Chalk surface (Figure 2), through which the Crossrail tunnels were anticipated to pass. Drift filled hollows are diapiric-shaped depressions, as much as 70 m deep, filled with drift deposits (Berry 1979); the hollow to the south of the Limmo Shafts site is filled with Kempton Park Gravel to a depth of 30 m from the surface. Their origin may be a combination of fluvial scour (Berry 1979) and periglacial pingo formation (Hutchinson 1980) by sub-permafrost groundwater flow along faults (Toms *et al.* 2016). The location of two known drift filled hollows is shown in Figure 2 as a deep depression in the Chalk surface. A hollow is also evident close to the Limmo Shafts, although this may be an extension of the known hollow to the south.

During the Palaeocene, basement fault slip was dextral, and these anomalous rock head hollows may have originated as releasing-bend flower structures forming transtensional basins (Figure 2). Given the rapid change in water depth from near sea level during deposition of the Lambeth Group to the relatively deep water London Clay Formation, this dextral movement most likely occurred during deposition of the upper part of the Lambeth Group, the Harwich Formation and perhaps the A2 part of the London Clay Formation, approximately 54·0–54·5 Ma ago. The effect of recent basin inversion (Ghail *et al.* 2015) is apparent in the site data and will be discussed later.

FIGURES 2

The hydrogeology in the London Basin is characterized by the presence of two main aquifers: the upper aquifer and the lower aquifer. The upper aquifer consists of River Terrace and alluvial deposits and is recharged by the pluvial and superficial waters. The lower aquifer is regionally more important and consists of the Chalk, Thanet Sand together with the basal sands of the Lambeth Group, Upnor Formation. Both aquifers are separated by aquitards (London Clay and the clayey units of the Lambeth Group). The main source of recharge to the Lower Aquifer is the water that enters into the

Chalk in its existing outcrops North and South of London. Also, 2 km south of the site, the River Terrace deposits lie directly above the Thanet Sand, creating a direct connection that allows additional recharge. The granular strata in the Lambeth Group above the Mid Lambeth Hiatus (MLH), a regional erosional boundary and the Harwich Formation, have limited connection to the Lower Aquifer (Roberts et al, 2015)

The main direct effect of this is the possible connection of the Lower and Upper Aquifer through this feature, altering the local hydrogeology. Flow paths through faults and drift filled hollows provide hydraulic connectivity between the upper and lower aquifers across the site, which is hydrostatic from 101·0mATD.

2 Ground Investigations

2.1 Boreholes

Given this complex geological background and the scale of the structures a thorough site investigation was undertaken for the Crossrail project. The desk studies included collation of existing ground investigation data and four phases of ground investigation on site; including previous third party boreholes, 51 boreholes were examined during the investigation (Figure 3 and Table 1).

FIGURE 3

TABLE 1

Recovery in the boreholes was difficult with frequent core loss reported, even in the London Clay, and the observed variations in strata interface levels is consistent with faulting across the site, suggesting throws of between 4 to 7m.

Figure 4 shows a schematic geological cross section based on the ground investigation.

FIGURE 4

2.2 Hydrogeology and pumping tests

One of the most significant risks for SCL construction is the presence of high groundwater pressures in high permeability deposits of the Harwich Formation and Lambeth Group. Although the SCL tunnels were anticipated to be excavated entirely within London Clay, should the amount of cover between tunnel inverts and underlying permeable strata be reduced, base heave could occur. To mitigate this risk, dewatering of the Lambeth Group and Harwich Formation would be required, similar to the employed in other sites of the project (Linde-Arias *et a*l 2015).

This risk was greater for the excavation of the Main and the Auxiliary shafts, given that their formation levels were lower. The base of the Auxiliary Shaft was in the London Clay, only 4m above the top of the Harwich Formation, and the Main Shaft was in the Harwich Formation. The toe of the diaphragm wall of the Main Shaft is the clay of the Lower Shelly Beds and the Lower Mottled Beds , impeding the recharge of the sandy horizons above that level.

Therefore, in addition to the ground investigations, a comprehensive programme of pumping tests was carried out in the different strata: Harwich Formation, Sand Units in Lambeth Group (Above MLH), Upnor Formation, Thanet Sand and Chalk (Roberts et al, 2015). These tests were crucial for the design of the dewatering of the lower aquifer.

Table 2 summarizes these results.

TABLE 2

The pumping tests yielded some interesting peculiarities of the hydrogeology of Limmo site.

Firstly, during the tests in the Chalk and Thanet Sand, the response of piezometers above the MLH indicated connectivity between the Upper Lambeth Group/Harwich Formation and the Lower Aquifer.

Secondly, the results of the chalk pumping tests were sometimes inconsistent, with drawdown not always decreasing with distance away from the pumped well.

Finally, the pumping tests revealed strong regular tidal fluctuation.

Although the above behaviours in some cases could be the result of inaccurate readings or due to natural variations in piezometric levels, together they indicated the presence of numerous faults that create hydrogeological compartments separated by low permeability barriers and/or create vertical paths through the aquitards.

The analysis of the data allowed an estimate of permeabilities of 1×10^{-5} m/s for the Thanet Sand and 2×10^{-4} m/s for the Chalk. Storativity was determined as 0.003 for the Thanet Sand and 0.004 for the Chalk.

2.3 Geotechnical tests

Routine laboratory testing was performed on fine and coarse grained soil samples obtained from the boreholes, including classification and index tests, and routine strength tests. In all the units the index test results were typical for the London area. A exception to this was that at Limmo, the undrained shear strength (s_u) measurements were lower than those at other Crossrail sites, especially the minimum values. Figure 5 shows a comparison of the lower bound values for Limmo site with the rest of the East section of the Crossrail tunnel (Liverpool St-Pudding Mill Lane) and the West section (Royal Oak – Liverpool St.).

FIGURE 5

Given that the index properties, including mineralogy, are typical of London Clay, the clay matrix is probably unaltered. Hence, an increase in discontinuity frequency, probably through faulting, is likely to be the main reason for the low strength values. This was also borne out by poor core recovery of several ground investigation boreholes in the London Clay, Harwich Formation and Lambeth Group. This is not believed to be due to poor drilling practises as the wire line system with triple tube protection of the core was employed in the boreholes.

3 Direct Observations during Excavation

The excavation of the Main and Auxiliary Shaft and the SCL tunnels allowed the direct observations of the Quaternary Deposits, London Clay and the Harwich Formation.

3.1 Stratigraphy and types of soils encountered

Made Ground and Quaternary Deposits

These deposits were encountered between 107 m ATD and 97·5 m ATD during the excavation of the shafts. The made ground is approximately 6 m thick and consists of black or grey silty, gravelly clay, often with organic matter or artificial materials and occasional fragments of bricks and wood. Numerous fragments of wood piles were extracted. At approximately 104mATD during excavation of the Auxiliary Shaft, the foundations of a previous structure, probably the remains of former ship building industries, were exposed, causing difficulties for the installation of some of the sheet piles.

The alluvium deposits were encountered between 101 m ATD and 97·5 m ATD. These consist of soft grey clay, sometimes sandy and with pockets of organic material, overlying the River Terrace Deposits (Kempton Park Gravels). The contact has a slight eastward inclination (approximately 3° to 5°) in the Auxiliary Shaft and is a clayey, sandy to very sandy, medium to coarse flinty gravel.

London Clay Formation

London Clay was encountered in the shafts and the SCL tunnels, which were excavated wholly within the Formation. The upper 2 m (from 93.5 up to 95.55 m ATD) is weathered and consists of firm grey clay, characteristically disturbed and with a lack of discontinuities. The unweathered London Clay is an over-consolidated, stiff clay. The formation is divided into a series of units (King, 1981), of which the A2 and A3 are encountered at the Limmo site. The boundary between these two units is easily recognized by the increase in silt content and the absence of claystones in the A2.

Fissures are a common feature in the London Clay formation. Usually, they are regarded as of synsedimentary or lithogenic origin. In the Limmo area the spacing is quite small, ranging from medium to extremely closely spaced. Polished and slickensided surfaces (commonly known as '*greasybacks*') were encountered but no trend in the orientation was identified.

Joints, defined as discontinuities longer than 1 m and probably tectonic in origin, are also very frequent. They are usually planar and polished, occasionally slickensided. Apertures range between 0.1mm and 1 mm, and are sometimes filled with a soft clay. Joints are typically spaced at 100 mm to 2m intervals. Discontinuity orientations were recorded during excavation of the main shaft (Figure 6). The primary set is sub-vertical, striking WNW-ESE, with a second set striking N-S. However, discontinuities may strike in any direction with dips as low as 40° to 60°.

FIGURE 6

Harwich Formation

The Harwich Formation was only encountered during the excavation of the Main Shaft, where it is a thin 0·6 m to 1·7 m thick stratum consisting of two different facies. One of these is a dark grey to very light greenish-grey slightly sandy clay representing the Swanscombe Member, which also contains rare calcrete concretions with a thickness of approximately 200mm. They are described as a moderately strong light grey limestone with occasional white fine gravel sized shell fragments.

The other is the Oldhaven member, represented by either a fine to medium dense brown sand with many white shell fragments or by a moderately strong light grey coarse grained shelly sandy limestone with rare rounded coarse gravel of black flint.

4 Faulting

4.1 Observed Faults

Desk studies and ground investigation data meant that faulting was anticipated at the Limmo site: the variation in the elevation of the boundaries between different strata is a clear indicator. Figure 7 shows an estimation of the contours of the base of the London Clay formation using the boreholes, that suggest the presence of faults especially to the south of the shafts.

FIGURE 7

Despite the above, it proved very difficult to locate the faults in the borehole cores. Even during the SCL works the relative homogeneity of London Clay, with no detectable compositional contrast, made the detection of faults very difficult. Also, faults are complex structures with different elements such as the slip surface or fault core that accommodates the majority of the strain and the surrounding damage zone, with low strain and subject to brittle deformation. However, three faults were inferred directly from observations made during the works.

Main Shaft Westbound Launch. Chainage 10

Between Chainages 9 to 12 a ~1 m band of highly fractured clay was encountered (Figure 8), with an orientation of approximately 70/150 (dip/azimuth). It was assumed to be a fault, but its slip direction could not be estimated.

FIGURE 8

Auxiliary Shaft Eastbound Launch. Chainage 12

The Eastbound Launch tunnel excavated from the Auxiliary Shaft started with the top heading completely in the A3. Between Chainage 10 and 12 a change was detected, with the A2 unit in the top heading instead of the A3 as previously, implying a fault displacement of several metres. This was detected by the absence of claystones and the increase of silt content.

Main Shaft

In the SCL tunnels west of the Main Shaft, the A2/A3 boundary was encountered higher than in the SCL tunnels to the east of the shaft by approximately 1.5m. This indicates the possible presence of a fault in the Main Shaft.

5 Geological Interpretation

The faults, fissures and differences in levels across the Limmo area may best be understood in light of the wider geological context detailed earlier. Inversion of the London Basin reactivated the basement strike-slip faults in a sinistral sense, so that what had been a transtensional releasing bend during the Palaeocene is now a transpressional restraining bend. The oblique normal faults of the flower structure below the London Clay Formation reversed and propagated into the previously un-faulted younger sediments, generating new compressional flower structures above each of the reactivated faults below, resulting in considerable structural complexity across the site (Figure 9)

FIGURE 9

Repetition of River Terrace Deposits in one of the boreholes (B254) indicates that the faults here have been active within the last ~100ka. InSAR data (Maso*n et al*. 2015) show strike-slip displacements close to the Limmo area of ~1·5 mm a^{-1} over recent decades but it is not clear whether the faults here are active in the present day. If they are, these faults will translate strike-slip displacement into reverse movements of approximately the same magnitude and hence the running tunnels may experience a shear of up to 150mm in the next 100 years, most likely accommodated by creep of the soil around the tunnels rather than displacement of the tunnels themselves. Whether or not these faults are creeping, they remain lines of structural weakness in the ground and conduits for groundwater flow.

Figure 10 represents an idealised block of this structure for clarity

FIGURE 10

6 Hydrogeology

After the ground investigation, it was concluded that it was necessary to install deep wells in the Thanet Sand and the Chalk to reduce the groundwater pressures in the Lower Aquifer in order to avoid uplift in the base of the Main Shaft. In the Auxiliary Shaft, the risk of uplift failure from the groundwater pressure at the top of the Harwich Formation was mitigated with passive wells.

The piezometers installed to monitor the drawdown initially showed hydrostatic continuity between the London Clay and Thanet Sand Formations (Figure 11).

FIGURE 11

However, the dewatering from the Thanet Sands and the Chalk has altered this pattern, with dewatering having a greater effect in the lower aquifer (in the basal sands of the Lambeth Group and Thanet Sand Formation). Piezometers in the Thanet Sand Formation show less drawdown because of their greater distance from the Main Shaft, where most of the pumps were installed. Piezometers in the Harwich Formation and the lower part of the London Clay were slightly under-drained, reaching hydrostatic equilibrium with the lower aquifer. Instruments installed at higher levels in the London Clay formation were not affected by the dewatering.

Hydraulic continuity between the upper and lower aquifers was a concern prior to the excavation of the tunnels, but no water was encountered in the SCL tunnels except for a slight seepage in the launch adits in the western part of the site, which are in close proximity to the River Lea. The flow of water, approximately 1l/min was accommodated through a pvc drain

7 Difficulties During SCL Works

During construction of the SCL works, localised face instability occurred. Although primary lining deformation was consistently lower than anticipated, the presence of fissure sets created the conditions for several localised failures, behaving similarly to a fractured rock mass. Exclusion zones were carefully implemented during SCL tunnelling activities and the use of spiles on alternate top headings also ensured the tunnels were constructed safely with ground instability reduced. Spiles are steel bars that are inserted a way of pre-suppor the excavation.

7.1 Bench failures.

The tunnelling sequence was of top heading, bench and invert. The bench stage resulted in a sub-vertical slope approximately 2.5 m high and several episodes of slope instability occurred during its excavation. The most frequent were planar type failures along polished joints (*greasybacks*), which occurred when joints daylighted in the excavation with dip angles sufficiently high (>45°) for the bench to become unstable within hours (Figure 12). These failures were particularly prevalent in the western section of the site and may therefore be associated with the faults and structural weaknesses exploited by the River Lea.

FIGURE 12

In some cases it was not possible to batter the slope sufficiently as there was a requirement for a minimum separation between bench and top heading. Pocket excavation and increasing the thickness of the 75mm sealing layer were some of the ‘tool box’ actions implemented.

In another instance, a local increase in the frequency of joints and fissures led to a rotational failure. As a consequence, the clay behaved similarly to a blocky rock mass (Figure 13).

FIGURE13

These instabilities of the bench stage reduced the rate of progress of the excavation.

7.2 Top Heading instabilities

The presence of discontinuities also impacted the stability of top headings. There were numerous examples of wedge failures during the excavation. Figure 14 shows an example of a localised wedge fall from the top heading face that occurred as a result of the intersection of three discontinuities.

FIGURE14

Although the stability of the tunnel was not at risk, these phenomena could result in accidents for the operatives and it was identified as a safety risk. Several risk reduction actions were put in place to mitigate face instability. Geotechnical logs were made of each excavated face, including descriptions of discontinuities and the installation of 35 mm rebar spiles to pre-support the excavation was made mandatory by the designer to avoid failures in the crown and outside the face. The spiles were driven in from lattice girders in the top headings, required in the temporary condition because of the close proximity of the two running tunnels in faulted ground, and an exclusion zone was implemented until the required sprayed concrete early strength was achieved. This ensured that personnel were not put at risk during excavation and spraying. Pocket excavation was used on encountering large scale discontinuities to mitigate the risk of face instability. It consists of reducing the area of the excavation by splitting the face into 2 or 3 smaller section that are excavated sequentially.

8 Conclusions

The information obtained during the ground investigation for the Limmo site suggested the presence of faults. Among others, some of the indications were: sudden changes in the elevation of boundaries between strata, low recovery in some of the boreholes in the London Clay, presence of barriers of low permeability in the pumping tests.

The Limmo tunnels were excavated within the London Clay Formation, normally a stiff over-consolidated clay that in the Limmo area is heavily fissured with numerous discontinuities more than 1000mm long forming several distinct joint sets. These discontinuities affected the design by causing the undrained shear strength to be much lower than usually expected for London Clay.

The faults, with throws between 4 and 7m, that are inferred to be part of a transpressional restraining bend flower structure overlying an older transtensional flower structure reactivated during present day inversion of the London Basin.

As well as weakening the ground, the faults, fissures and joint sets also provide hydraulic connectivity between the upper and lower aquifer, although this did not lead to significant inflows of water during excavation.

The discontinuities and joint sets led to several episodes of instability during the excavation, requiring a number of measures including face logging, pocket excavation, spiling and implementation of exclusion zones to mitigate against this risk, which enabled the tunnels to be constructed safely and on programme.

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Figure Captions

Figure 1. Location of the Limmo Site

Figure 2. Limmo Shafts area OS map plotted on uppermost chalk surface, showing approximate orientation of the active sinistral wrench fault identified in Mason et al. (2015). Localised hollows in the chalk surface may be indicative of drift filled hollows, a common geohazard in the Limmo Peninsular. Contour interval is 2 m; box dimensions are 2000 (E) × 2000 (N) × 70 (H) m. Map based on Ordnance Survey Data © Crown copyright/database right 2015; model constructed in Move 2016.

Figure 3. Boreholes in Limmo Site and some of the faults inferred during the pre-construction stage. Numbers in brackets show the elevation of the bottom of the London Clay Formation.

Figure 4. Geological cross section in Limmo site.

Figure 5. London Clay lower bound values of the undrained shear strength obtained with for Limmo and for all other Crossrail sites.

Figure 6. Stereogram polar density plot of discontinuity orientation

Figure 7. Estimated contours of the base of the London Clay formation across the Limmo site

Figure 8. Shear zone encountered between Chainages 9 to 12.

Figure 9. Simplified geological model of the Limmo Shafts area; the nearer of the shafts (both in orange) is 30 m in diameter and 44 m deep; the farther is 27 m in diameter and 39 m deep. The 7·1 m diameter running tunnels are at 73 m ATD. Two steep reverse faults (dip-azimuth of 70-150) are shown propagating up from one of the faults in the Chalk (shown in Figure 2); the change in levels to the SE (far right) is likely caused by a third similar fault, which for clarity is not shown. Minor faults and periglacial features are omitted. The northern fault intersects the tunnel, as was observed (Figure 6), while the southern fault causes the observed repetition of strata in borehole B254. The coloured surface from blue at 70 m to white at 89 m ATD is the top of the London Clay Formation A2 layer (King, 1980) , generated by inverse distance weighted borehole data (rotary with tracks shown and percussive as spot points). The borehole tracks are coloured by strata, above the London Clay these are Made Ground in red and River Terrace Deposits in beige. Notice that the SCL tunnels are mostly in A3 but the exterior TBM tunnels are in A2. Model constructed in Move 2016.

Figure 10 Idealised section and block diagram illustrating the propagation of fractures associated with a bend on a strike-slip fault, through younger sediments. A bend (A) on a basement strike-slip fault causes a releasing bend pull-apart basin (idealised at B) in the Chalk, probably during early Tertiary extension. This is reversed by recent inversion (shortening) aligned slightly obliquely to the basement fault (note that the straight part of the blue and red fractures is oriented differently to the straight line part of the green fracture), and generates new restraining bend push-up structure (C and D) in the Tertiary sediments (Lambeth Group and London Clay Formation), one new push-up structure for each fracture in the Chalk pull-apart structure. Note the complexity this generates at (D); in reality, many fractures would have formed in the pull-apart basin (B), each generating a push-up structure themselves contain many fractures. Hence the ground in these areas becomes intensely fractured and weakened.

Figure 11. Profile of pore water pressure in newly installed piezometers, pre- (circles) and post-dewatering (triangles)

Figure 12. Planar failure during bench stage

Figure 13. Circular failure during bench stage

Figure 14. Wedge failure during top heading stage

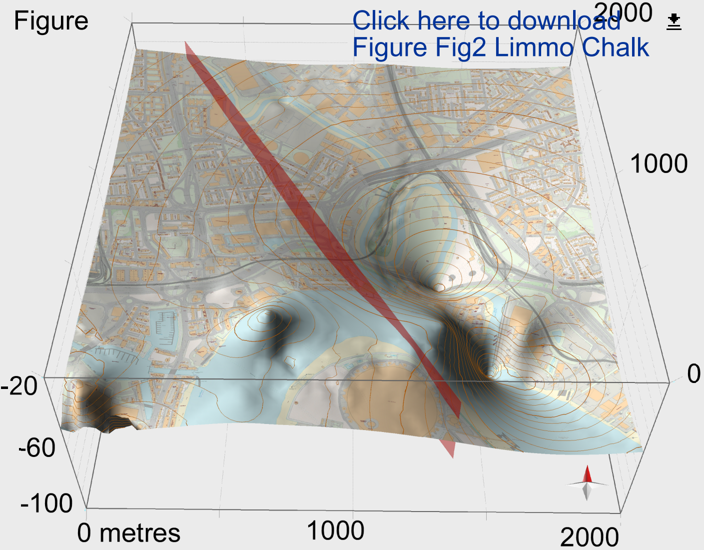
Table 1. Units encountered in the boreholes and the range of elevations of the top and base.

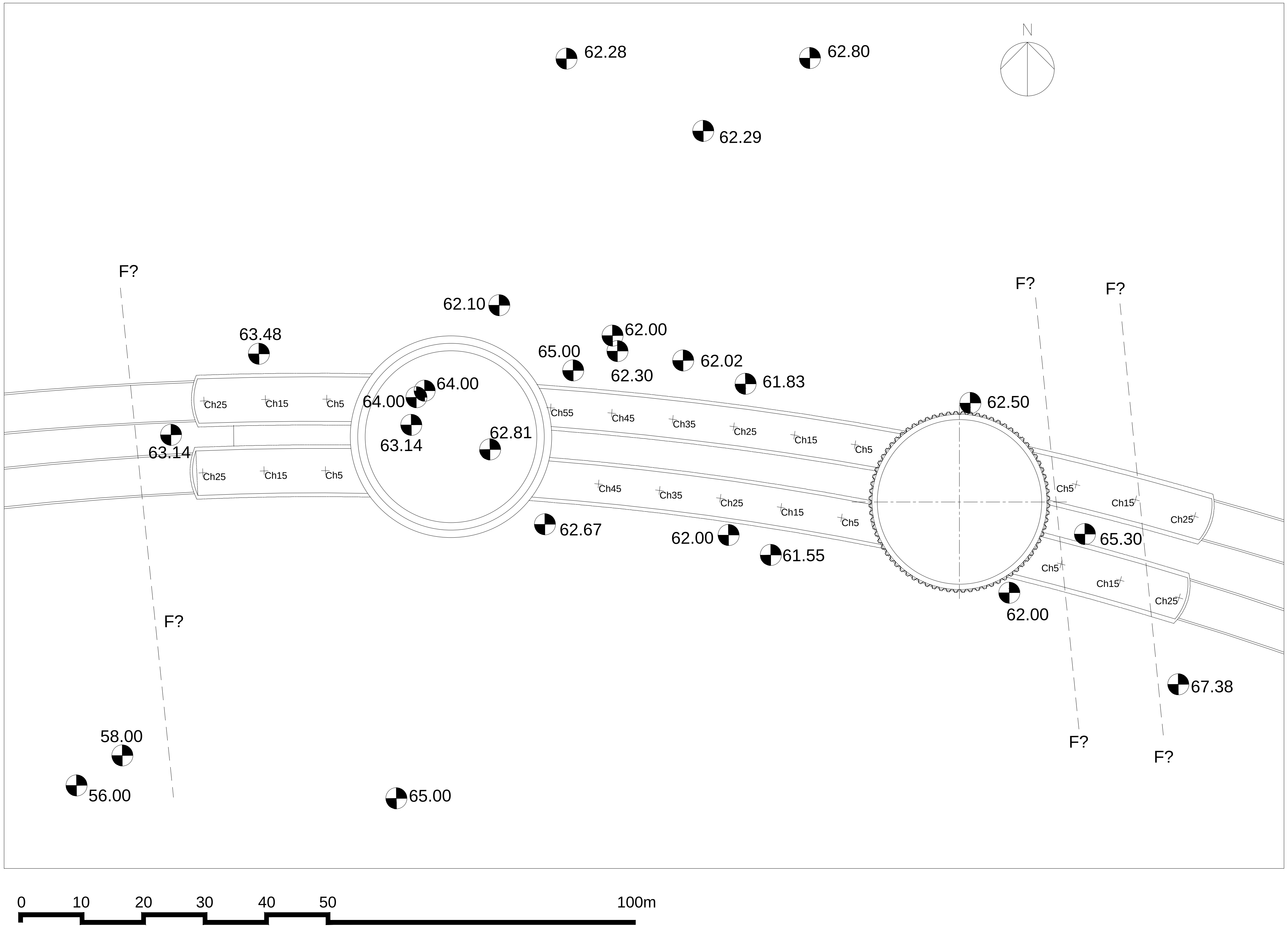
Table 2. Pumping test regime.

Stratum		**Top (mATD)**	**Base (mATD)**
Alluvium/Kempton Park Gravel		100.0 to 96.0	85.5 to 95.5
London Clay Formation		95.5 to 85.5	75.2 to 56.6
Harwich Formation		75.2 to 56.6	74.2 to 61.6
Lambeth Group	Sand Unit	74.2 to 60.4	56.9 to 56.6
	Sand Channels	56.9 to 56.6	61.8 to 55.6
	Laminated Beds	74.2 to 59.8	68.8 to 55.1
	Lower Shelly Beds	68.8 to 55.1	66.6 to 53.2
	Lower Mottled Beds	66.6 to 53.1	59.9 to 48.1
	Upnor Formation	59.9 to 48.1	57.1 to 44.6
Thanet Sand Formation		57.1 to 44.6	30.2 to 27.7
Chalk		30.2 to 27.8	N/A

Stratum	**Well depth (m)**	**Flow rate at steady state (l/s)**	**Pumping**
Harwich	47.5	0.18	69 hrs
Harwich	49.3	0.14	46 hrs
Lambeth	55.5	0.4	39 hrs
Lambeth	57	0.52	42 hrs
Thanet	79	2.5	40 hrs
Chalk	114	20	9 days 10 hrs

Figure

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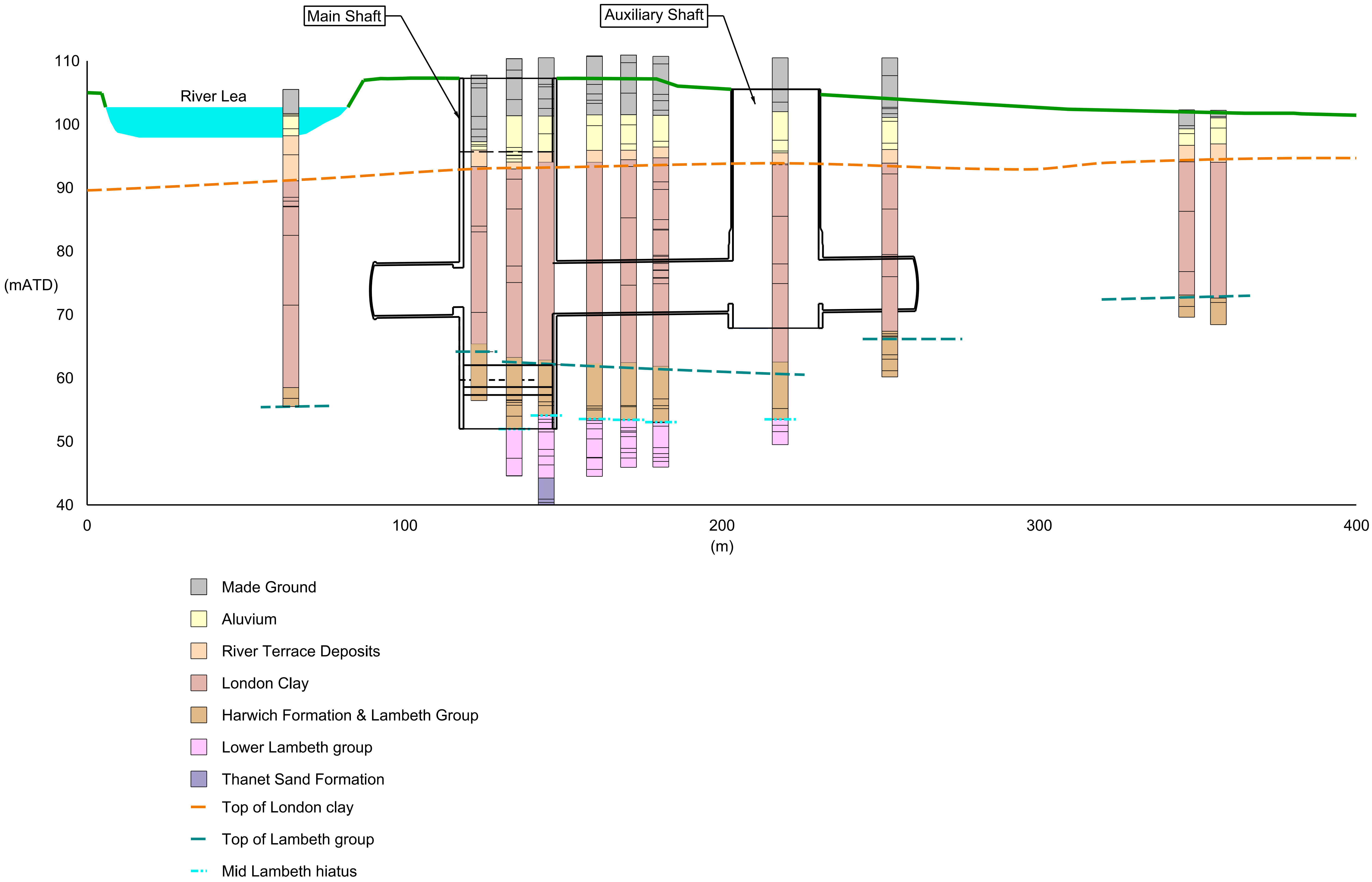
Main Shaft
Auxiliary Shaft
River Lea
110
100
90
80
(mATD)
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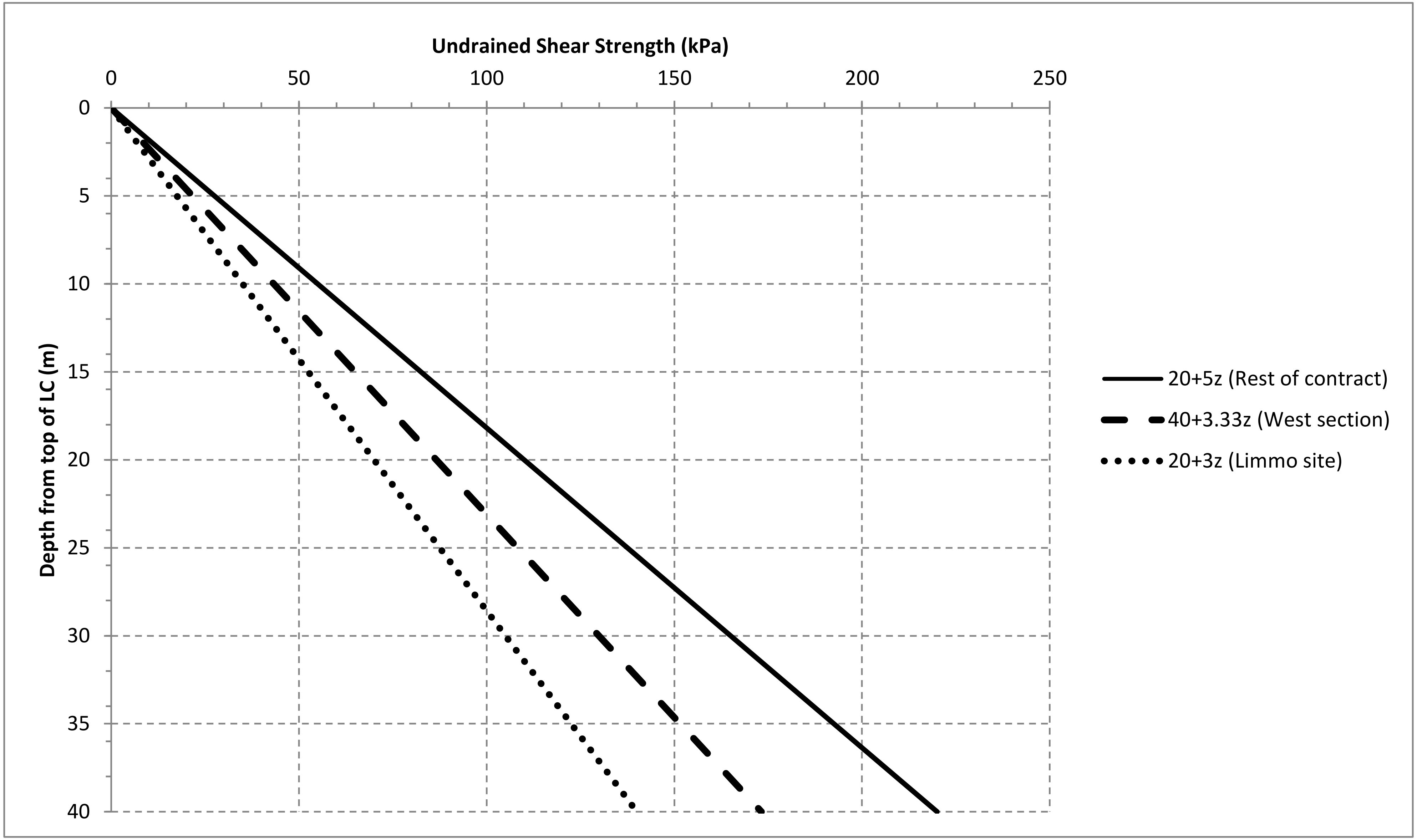
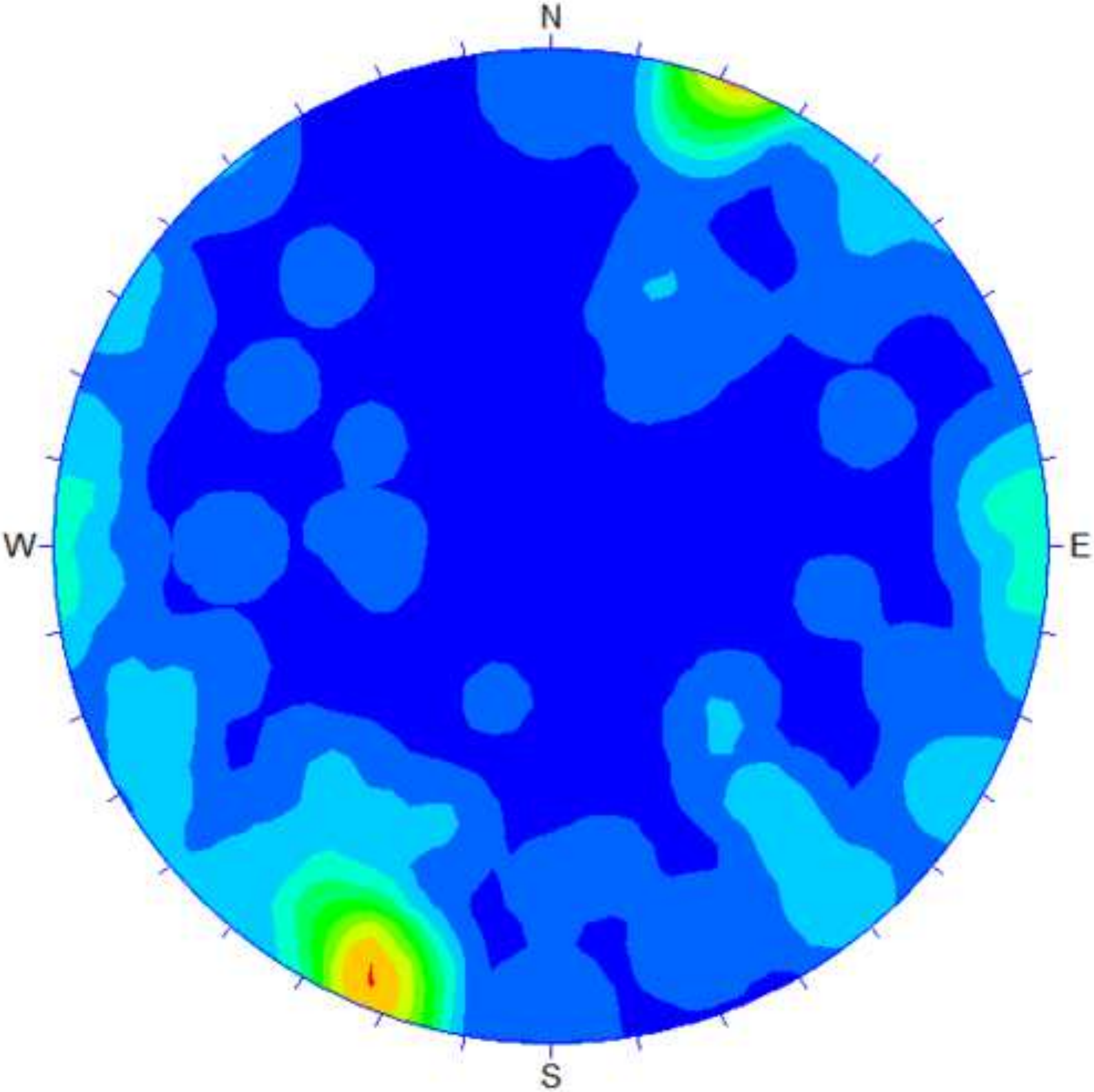
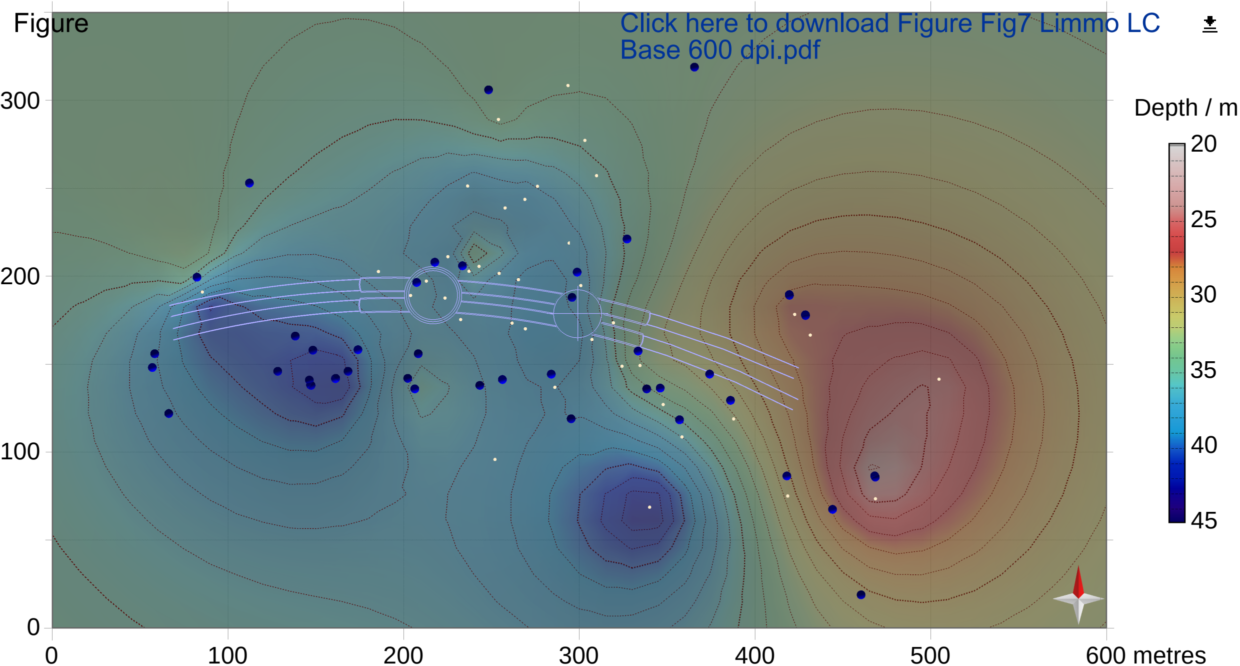
300
400
(m)
Made Ground
Aluvium
River Terrace Deposits
London Clay
Harwich Formation & Lambeth Group
Lower Lambeth group
Thanet Sand Formation
Top of London clay
Top of Lambeth group
Mid Lambeth hiatus


Undrained Shear Strength (kPa)
0
50
100
150
200
250
Depth from top of LC (m)
0
5
10
15
20
25
30
35
40
20+5z (Rest of contract)
40+3.33z (West section)
20+3z (Limmo site)


N
W
E
S

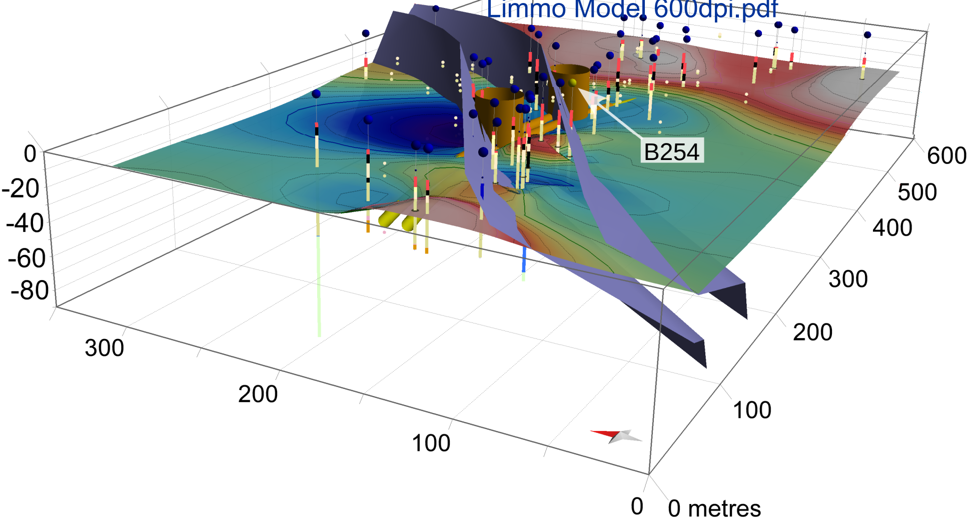
Figure

Click here to download Figure Fig7 Limmo LC Base 600 dpi.pdf

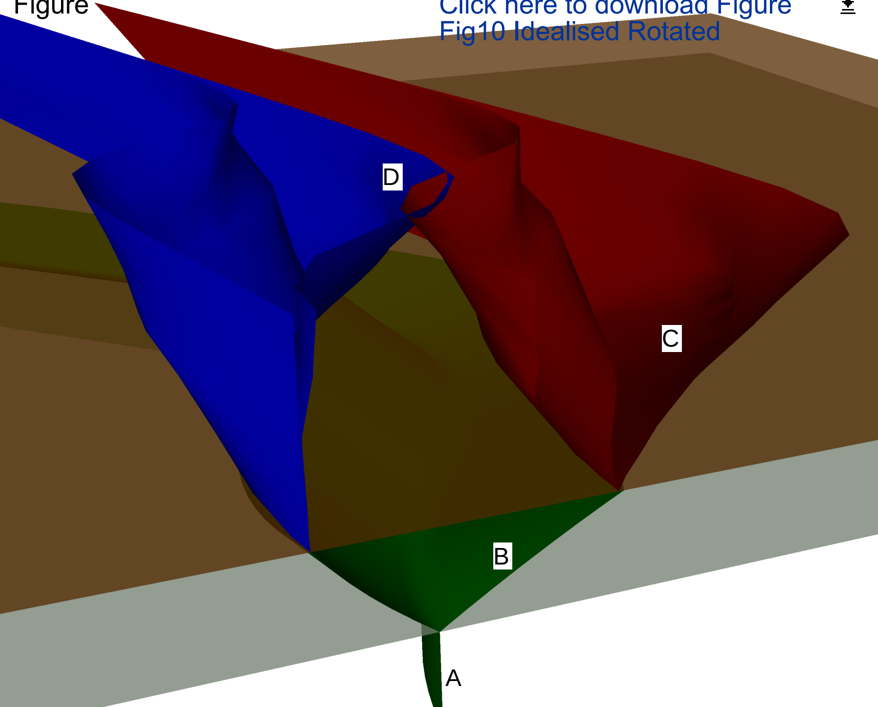


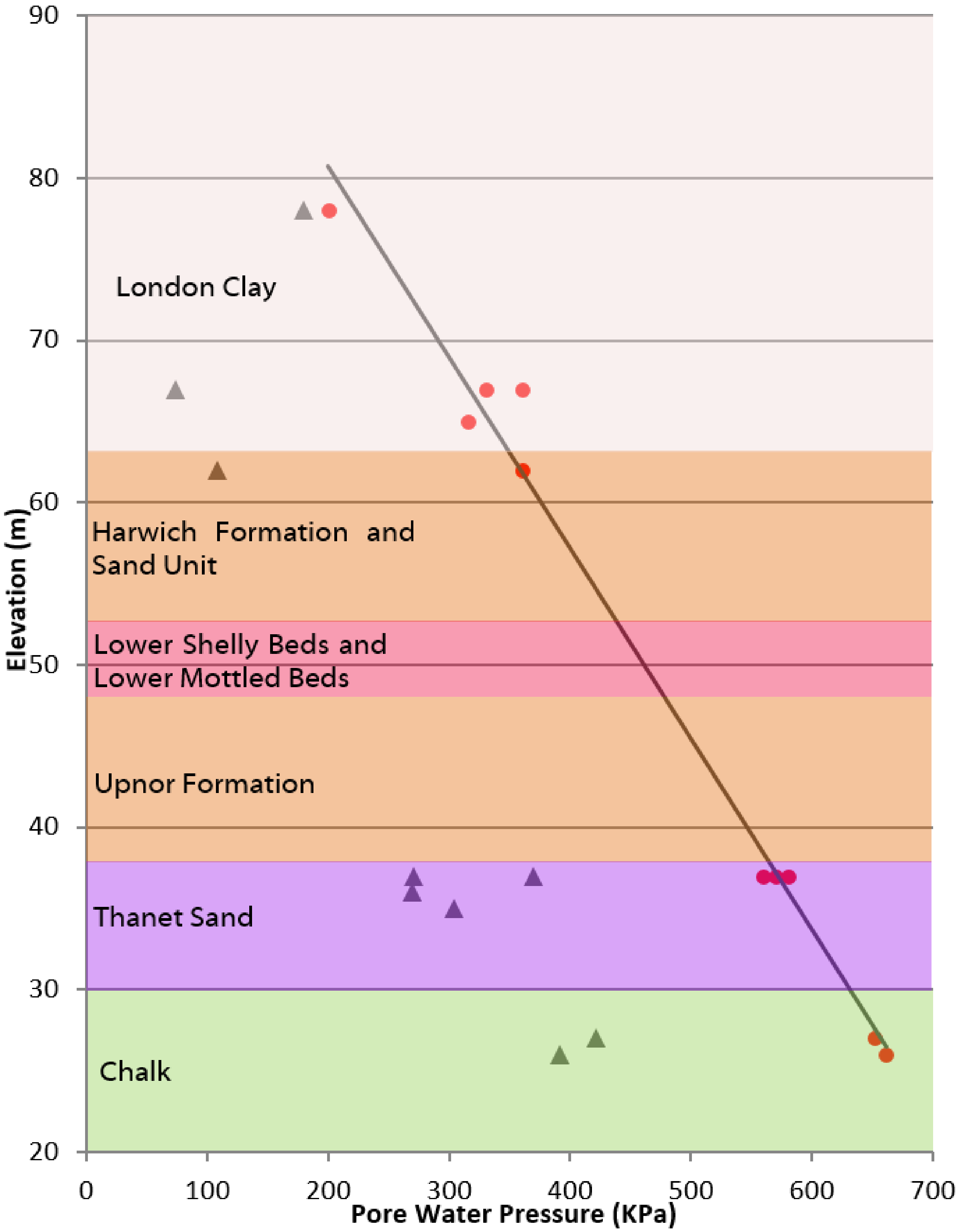

Shear Zone

Figure

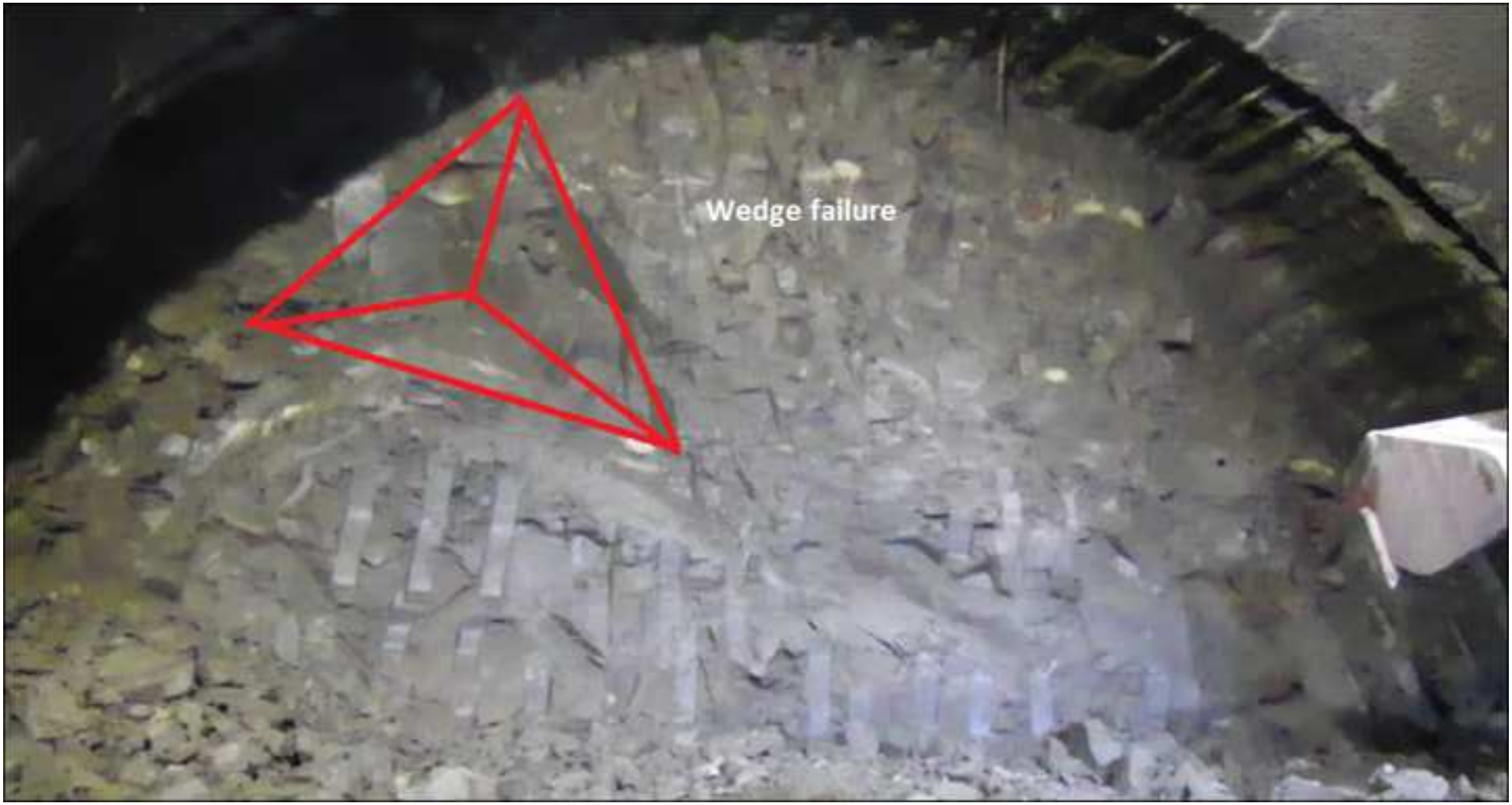


Figure




90
80
70
60
50
40
30
20
Elevation (m)
London Clay
Harwich Formation and Sand Unit
Lower Shelly Beds and Lower Mottled Beds
Upnor Formation
Thanet Sand
Chalk
0
100
200
300
400
500
600
700
Pore Water Pressure (KPa)


10/08/2012


Wedge failure