TUBULAR KING PILE FOUNDATION SYSTEM

- Robust and Resilient Foundation System with High Cost Efficiency -

Vol.1 Design

GIKEN

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Chapter 1 Introduction

The purpose of this document is to provide model practice guidelines for the design of the Tubular King Pile Foundation to be installed, using the Press-in Piling Method.

The press-in piling method is commonly used worldwide because of its very quiet operation, ultra low vibration, and flexibility of sizes to suit different wall properties and subsoil conditions.

The main attributes of the Tubular King Pile Foundation are efficiency of physical properties and versatility. The Tubular King Pile Foundation comprises steel tubular piles as the primary foundation elements and incorporating additional upper wall elements on top of the steel tubular piles. The efficiencies of physical foundation properties can be optimised in view of the flexibility of pile size and the spacing of tubular piles for the ground conditions and the form of the loading.

Chapter 2 Foundation Configuration

Tubular King Pile Foundation is a combined foundation with great bending stiffness, which incorporates the following elements.

1. **Steel Tubular Piles**: Primary elements (High modulus main structural elements)
   Tubular piles resist lateral load when used as a retaining wall or barrier, and vertical loads when used as bearing piles.
2. **Upper Wall**: Wall elements (Soil-retaining and load-transferring elements)
   The Upper wall transfers soil pressure, vertical loads and horizontal dynamic loads to the tubular piles.

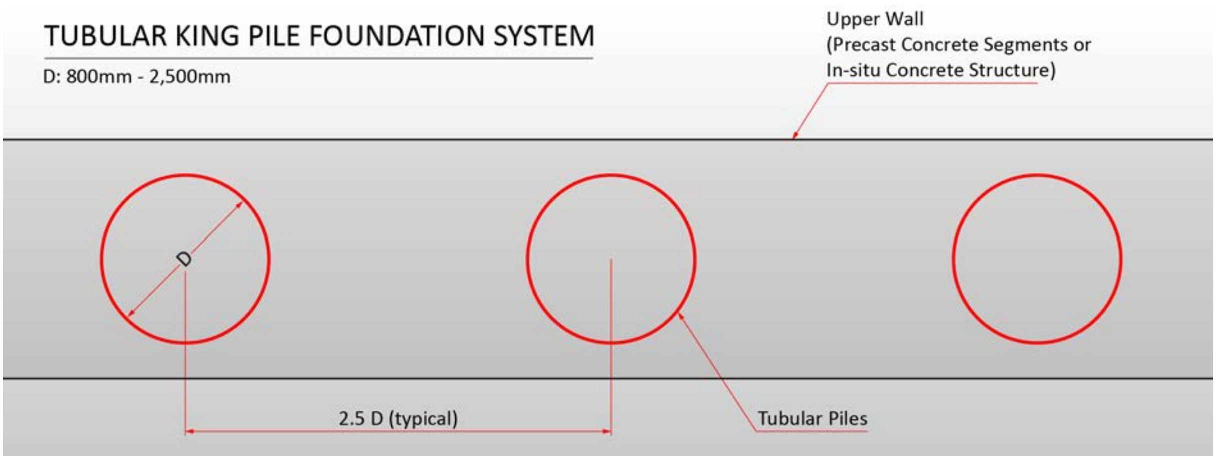


Figure 1. Foundation Configuration

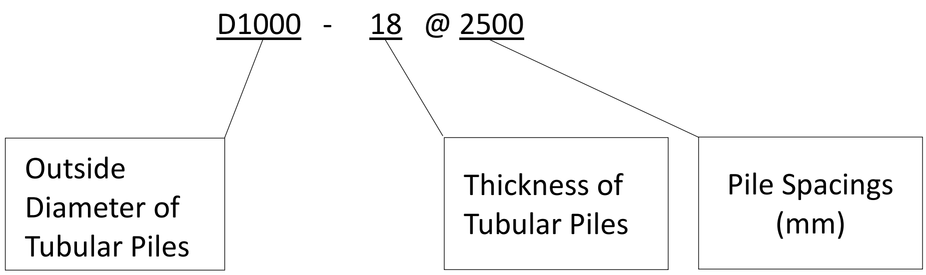
Chapter 3 Foundation Properties

The steel tubular piles of the Tubular King Pile Foundation are installed to a depth necessary to achieve the required passive toe resistance while the upper wall can be incorporated only above the steel tubular piles to act as a barrier for the soil or dynamic loads.

The steel tubular piles and upper wall are integrated with reinforcement bars or shear connectors to achieve effective load transfer.

3-1 Denomination of the Tubular King Pile Foundation

The profiles of the Tubular King Pile Foundation are related to their dimension as follows:-



3-2 Properties of Tubular King Pile Foundation

Tubular King Pile Foundation	Outside Diameter (mm)	Wall thickness (mm)	Inside Diameter (mm)	Spacing (mm)	Section Modulus Z (cm^3)	Section Modulus Z (cm^3/m)	Allowable Stress (N/mm^2)	Moment of Inertia I (cm^4)	Moment of Inertia I (cm^4/m)	Elastic Modulus E X 10^8 (kN/m^2)	E I (kNm^2/m)	Moment Capacity (kNm/m)	Mass per m of pile (kg/m)	Mass per m^2 of wall (kg/m^2)
D800 - 12 @ 2000	800	12	776	2,000	5,766	2,883	231	230,632	115,316	2.05	236,398	665	233	117
D800 - 14 @ 2000	800	14	772	2,000	6,676	3,338	231	267,050	133,525	2.05	273,727	770	271	136
D800 - 16 @ 2000	800	16	768	2,000	7,573	3,786	231	302,907	151,453	2.05	310,479	874	309	155
D800 - 18 @ 2000	800	18	764	2,000	8,455	4,228	231	338,207	169,104	2.05	346,662	976	347	174
D1000 - 12 @ 2500	1,000	12	976	2,500	9,091	3,636	231	454,544	181,818	2.05	372,726	839	292	117
D1000 - 14 @ 2500	1,000	14	972	2,500	10,542	4,217	231	527,116	210,846	2.05	432,235	973	340	136
D1000 - 16 @ 2500	1,000	16	968	2,500	11,976	4,790	231	598,797	239,519	2.05	491,014	1,105	388	155
D1000 - 18 @ 2500	1,000	18	964	2,500	13,392	5,357	231	669,596	267,838	2.05	549,069	1,236	436	174
D1000 - 20 @ 2500	1,000	20	960	2,500	14,790	5,916	231	739,518	295,807	2.05	606,405	1,365	483	193
D1000 - 22 @ 2500	1,000	22	956	2,500	16,171	6,469	231	808,572	323,429	2.05	663,029	1,493	531	212
D1200 - 14 @ 2800	1,200	14	1,172	2,800	15,288	5,460	231	917,281	337,600	2.05	692,080	1,261	409	146
D1200 - 16 @ 2800	1,200	16	1,168	2,800	17,385	6,209	231	1,043,072	372,526	2.05	763,678	1,434	467	166
D1200 - 18 @ 2800	1,200	18	1,164	2,800	19,460	6,950	231	1,167,577	416,992	2.05	854,833	1,605	525	187
D1200 - 20 @ 2800	1,200	20	1,160	2,800	21,513	7,683	231	1,290,805	461,002	2.05	945,054	1,774	582	207
D1200 - 22 @ 2800	1,200	22	1,156	2,800	23,546	8,409	231	1,412,765	504,559	2.05	1,034,345	1,942	639	228
D1200 - 25 @ 2800	1,200	25	1,150	2,800	26,556	9,484	231	1,593,346	569,052	2.05	1,166,556	2,190	724	258

Table 1. Foundation Profiles

Chapter 4 Foundation Wall Design

4-1 General

Tubular piles, as the primary elements of the Tubular King Pile Foundation system, act as the retaining elements against the earth and water pressures transferred via the secondary element, i.e. RC upper wall. Thus, the design of the wall system can be undertaken as a continuous retaining wall.

One of the advantages of this system is that, dissimilar to conventional steel sheet piled walls, the differential pore water pressure between the active and the passive sides can be considered negligible below the underside of the RC upper wall since there are sufficient gaps between the tubular piles for the groundwater to be equalised between the sides.

4-2 Embedded Depth of Tubular King Pile Foundation

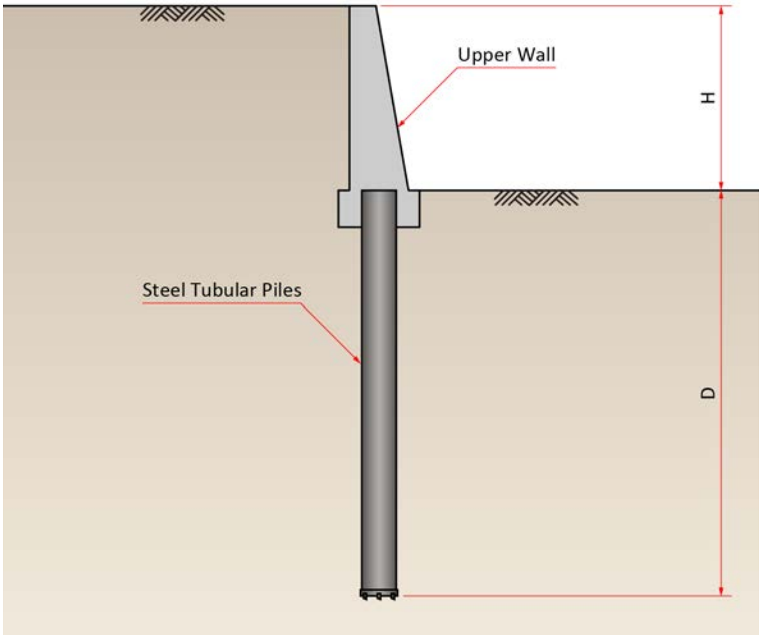


Figure 2. Cross Section (Retaining Wall)

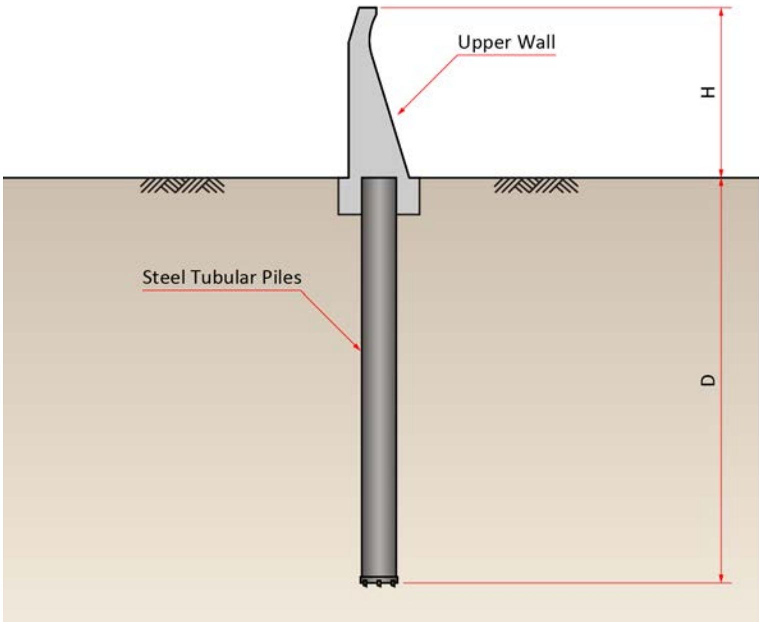


Figure 3. Cross Section (Barrier)

4-2-1 Embedded Depth of Tubular Piles D_{pri}

Limit equilibrium methods can be used to assess the required embedded depth of tubular piles. The methods use an approach based on soil and groundwater parameters that tend towards worst credible values and assume that the full strength of the ground is mobilised uniformly around the wall so that the wall is at the point of collapse.

Design parameters could govern the embedded depth of the tubular piles are:

- stratigraphy;
- soil unit weight;
- soil strength (c_u, c', ϕ');
- groundwater levels;
- surcharge loads;
- horizontal impact loads;
- retained height;
- durability/corrosion rates; and
- propped or cantilevered.

4-2-2 Embedded Depth of RC Upper Wall D_{uw}

The RC upper wall is only required from the retained surface to the formation level. In practice the base of the upper wall is extended below the formation level to take into account unplanned excavation. Besides, careful consideration should be given to drainage design of the RC upper wall to minimise the occurrence of high differential water pressure.

4-3 Passive Mobilisation Mechanism

When the tubular piles are loaded laterally, distribution of the soil stresses can be simulated based on the Theory of Elasticity using the Boussinesq equation that considers a point load on the surface of a semi-infinite, homogeneous, isotropic, weightless, elastic half-space. The concept of the pressure bulb prepared from the Boussinesq's equation by Bowles [1996], as shown in Figure 4, is useful to visualise the pressure developed in the effective passive area.

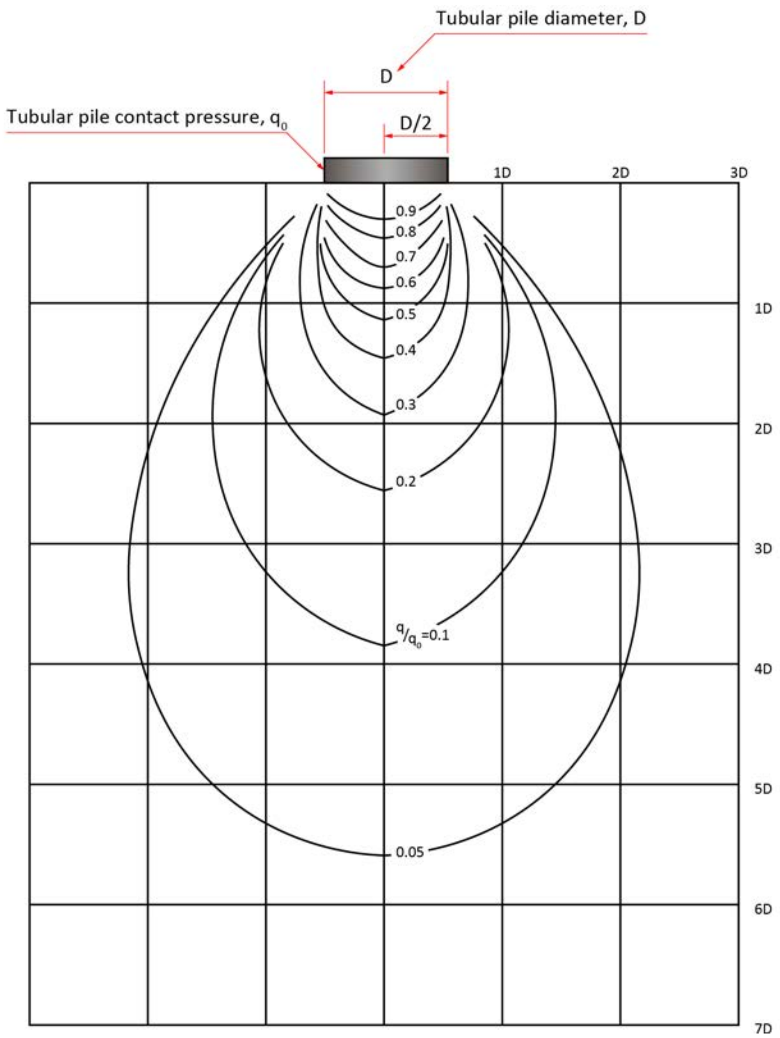


Figure 4. Pressure bulbs formed on the passive side of a tubular pile, showing the intensity of pressure q/q0,based on the Boussinesq equation (after Bowles [1996])

The lateral force transferred from the upper wall, resulting from the earth/water pressures and surcharge load and etc., are resisted by the passive pressure developed in the effective passive zone as schematically presented in Figure 5.

Though there is no simple relationship between the characteristics of the effective passive area (nD) and soil conditions as any relationship is dependent on the tubular pile size/spacing and on the nature and sequence of the strata, "nD" at a certain distance (H) in low strength cohesive soil is generally greater than that in dense cohesion less soil.

[1] Bowles, J.E. [1996] Foundation analysis and design - 5th edition, McGraw-Hill, Singapore.

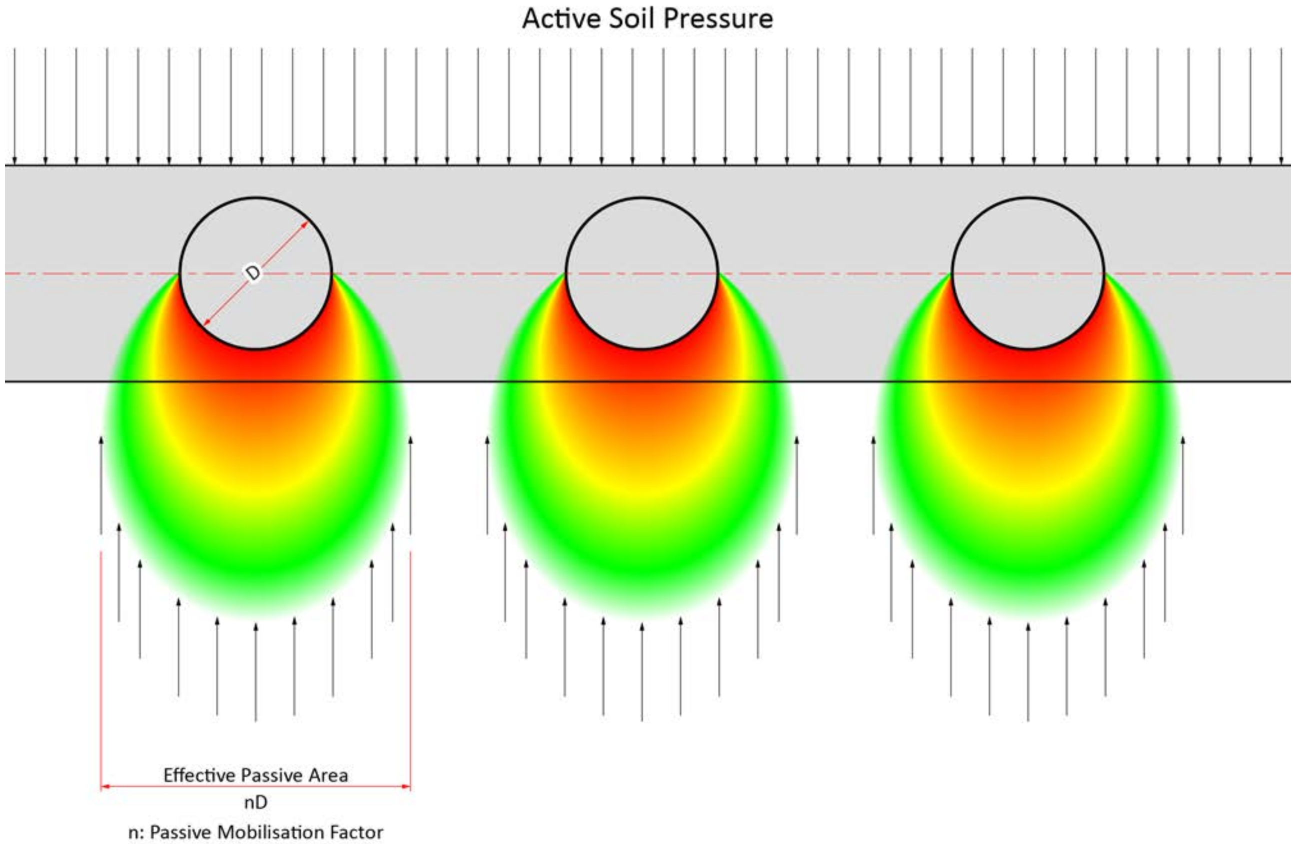


Figure 5. Schematic effective area for passive soil pressure

4-4 Durability

The effective life of the Tubular King Pile Foundation depends upon the combined effects of imposed stresses and corrosion.
Performance is clearly optimised where low corrosion rates exist at positions of high imposed stresses.

Eurocode 3: part 5 considers the end of the effective life of steel piles to occur when any part of the pile reaches the maximum permissible working stress as a result of loss of section due to corrosion.

The tubular piles may be exposed to different combinations of environments. The following table indicates the mean loss of thickness due to corrosion for these environments in temperate climates over a given life span.

4-4-1 Loss of thickness (mm) per face due to corrosion of steel tubular piles in soils, with or without groundwater

Environments	5 years	25years	50years	75years	100years	125years
Undisturbed natural soils (sand, silt, clay, schist…)	0.00	0.30	0.60	0.90	1.20	1.50
Polluted natural soils and industrial sites	0.15	0.75	1.50	2.25	3.00	3.75
Aggressive natural soils (swamp, marsh, peat…)	0.20	1.00	1.75	2.50	3.25	4.00
Non-compacted and non-aggressive fills (clay, schist, sand, silt…)	0.18	0.70	1.20	1.70	2.20	2.70
Non-compacted and aggressive fills (ashes, slag…)	0.50	2.00	3.25	4.50	5.75	7.00

Table 2. Corrosion Rates in Soil, with or without groundwater

Note1; Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the table should be divided by two.
Note2; The values given for 5 years and 25 years are based on measurements, whereas the other values are extrapolated.

Chapter 5 Design Case Study

5-1 Introduction

These calculations detail a design case study of the Tubular King Pile Foundation system forming a 7m-high permanent retaining structure for widening of motorway that has been constructed on an embankment fill. The retaining structure comprises steel tubular piles of 1000mm external diameter (with the wall thickness of 14mm) at 2.5m centres and a continuous reinforced concrete wall. The design life of the structure has been considered to be one hundred years.

The Geosolve WALLAP software has been used to analyse the retaining wall in accordance with BS EN 1997-1, based on factoring of surcharge loadings, soil strength parameters and an additional overdig allowance. The code is based on the use of limit equilibrium methods and uses an approach based on soil and groundwater parameters that tend towards worst credible values to develop an adequate margin of safety. The wall's cross section has also been verified against structural failure, using unfactored soil strength, factored surcharge loadings and an additional overdig allowance. These ultimate limit state analyses were followed by a serviceability limit state analysis, using unfactored soil strength and action, to determine the predicted wall deflection, based on WALLAP.

In order to estimate ground movements adjacent to the retaining walls soil/structure interaction analyses have also been carried out using a two-dimensional (2D) finite element (FE) software package "Plaxis".

Results of the design and associated findings will be presented in this section.

5-2 List of Design Standards and References

- Bond, A. and Harris, A. [2008] Decoding Eurocode 7, Taylor and Francis, London.
- Borin, D. [2007] WALLAP User's Guide, Ver. 5, Geosolve.
- British Standards Institution [1998] Highway parapets for bridges and other structures - Specification for vehicle containment parapets of metal construction, BS 6779-1.
- British Standards Institution [1999] Execution of special geotechnical work – Sheet pile walls, BS EN 12063.
- British Standards Institution [2004] Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings, BS EN 1992-1-1.
- British Standards Institution [2004] Eurocode 7: Geotechnical design, Part 1: General rules, BS EN 1997-1.
- British Standards Institution [2005] Eurocode 3: Design of steel structures, Part 1-1: General rules and rules for buildings, BS EN 1993-1-1.
- British Standards Institution [2007] Eurocode 3: Design of steel structures, Part 5: Piling, BS EN 1993-5.
- British Standards Institution [2010] Road restraint systems - Part 2: Performance classes impact test acceptance criteria and test methods for safety barriers including vehicle parapets, BS EN 1317-2.
- CIRIA C580 [2003]: Embedded retaining walls - guidance for economic design.
- Design Manual For Roads And Bridges [2001] Loads for highway bridges, BD 37/01, Vol. 1, Section 3, Part 14.
- Design Manual For Roads And Bridges [2006] Requirement for road restraint systems, TD 19/06, Vol. 2, Section 2, Part 8.
- Plaxis b.v. [2015] Plaxis 2D 2015 - Reference Manual.
- Plaxis b.v. [2015] Plaxis 2D 2015 - Material Model Manual.

5-3 Ground Conditions

5-3-1 Ground Model

Ground model adopted for the case study has the following geological formations:

a) Embankment Fill / Backfill

The Embankment Fill / Backfill comprises compacted granular materials, e.g. sand, gravel, crushed rock and crushed concrete. The material has been assumed as a dense granular soil.

b) Medium Dense Sand

The material is a layer of naturally deposited sand with relatively uniform medium dense consistency.

c) Stiff Clay

The material is a heavily overconsolidated stiff clay with a K_0 value of 1.5 and the thickness of the formation has been considered to be >20m.

The following stratigraphy has been established for the retaining wall analysis.

Embankment Fill	+7.0m AOD to 0.0m AOD
Medium Dense Sand	0.0m AOD to -5.0m AOD
Stiff Clay:	-5.0m AOD to -25.0m AOD

5-3-2 Geotechnical Design Parameters

A summary of the geotechnical parameters used for the retaining wall analysis is presented in Table 3.

Strata	Elevation (top of stratum mAOD)	Thickness (m)	Unit weight (kN/m^3)	Angle of Shearing resistance, φ'_{peak} (Deg.)	Effective cohesion, c' (kN/m^2)	Undrained shear strength, c_u (kN/m^2)	Drained Stiffness, E' (MN/m^2)	Undrained Stiffness, E_u (MN/m^2)	Drained Poisson's ratio, ν	Undrained Poisson's ratio, ν_u	K_0	Coefficient of permeability, K (m/s)	Dilatancy angle for drained analysis, ψ (Deg.)
Embankment Fill	7.0	7.0	19	38	0	-	10 + 5z	-	0.30	-	0.38	10^{-5}	8
Medium Dense Sand	0.0	5.0	19	35	0	-	25 + 5z	-	0.30	-	0.43	10^{-5}	5
Stiff Clay	-5.0	>20.0	20	20	10	100 + 7z	80 + 5.6z	100 + 7z	0.20	0.49	1.50	10^{-10}	12.5

Table 3. Summary of geotechnical parameters for the retaining wall analysis

Notes on design geotechnical parameters

1) z is the depth below top of each stratum.

5-3-3 Design Groundwater Levels

The groundwater table has been assumed at -0.5m AOD for the design life of the structure. Due to the presence of large gaps between the tubular piles, the differential water pressure between the active and the passive sides can be considered negligible below the underside of the RC upper wall.

It has been assumed that the highway surface water is drained to a sealed carrier pipe via kerbs and gullies. Besides, owing to the granular nature of the embankment fill materials, the groundwater level at the back of the RC upper wall is unlikely to build up. Hence, as summarised in Table 4, the design water levels on the active side have been assigned to 0.5m and 0.0m AOD for the worst credible and moderately conservative cases, respectively.

Design case	Active side [mAOD]	Passive side [mAOD]
Worst credible (ULS)	0.5	-0.5
Moderately conservative (SLS)	0.0	-0.5

Table 4. Design groundwater levels for the retaining wall analysis

5-4 Design Approach

5-4-1 Retaining Wall Analysis

The Geosolve WALLAP software (Version 6.05) has been used to analyse the retaining walls in accordance with Design Approach 1 in BS EN 1997-1 which requires the following analyses:

- A serviceability limit state (SLS) analysis using unfactored soil strength and action.
- An ultimate limit state (ULS) Combination 1 analysis using unfactored soil strength, factored surcharge loadings and an additional overdig allowance.
- An ultimate limit state (ULS) Combination 2 analysis using factored surcharge loadings, factored soil properties and an additional overdig allowance.

In order to estimate ground movements adjacent to the retaining walls soil/structure interaction analyses have also been carried out using the 2D FE software package, Plaxis 2D (ver. 2015.1). The behaviour of soils and structures during various construction stages and post-construction has been investigated using a "plain strain" deformation analysis mode, based on unfactored "undrained" and "drained" soil parameters.

The Plaxis analysis also enabled to calculate wall deflections and structural forces of individual members from the Tubular King Pile Foundation system separately, i.e. steel tubular piles and RC upper wall.

5-4-2 Partial Factors

The design uses safety factors obtained from BS EN 1997-1, summarised in Table 5. These factors are applied to both the actions as well as the material properties.

Design Approach 1				Combination 1			Combination 2			Reference in BS EN 1997-1:2004
				Set			Set			
				A1	M1	R1	A2	M2	R1	
Actions	Permanent	Unfavourable	γ_G	1.35			1			Table A.3
		Favourable	$\gamma_{G;fav}$	1			1			
	Variable	Unfavourable	γ_Q	1.5			1.3			
		Favourable	$\gamma_{Q;fav}$	0			0			
Material Properties	Angle of shearing		$\gamma_{\phi'}$		1			1.25		Table A.4
	Effective cohesion		$\gamma_{c'}$		1			1.25		
	Undrained shear strength		γ_{cu}		1			1.4		
	Unconfined strength		γ_{qu}		1			1.4		
	Weight density		γ_{γ}		1			1		

Table 5. Summary of partial factors used for design of retaining walls (after BS EN 1997-1)

The partial factor on variable unfavourable actions in DA1 Combinations 1 is 1.5. However, adopting this approach generates unrealistic and onerous load effects in the piles. According to retaining wall design detailed in Bond & Harris [2008] (Section 12.5.1 page 420), variable actions should be factored by 1.1 in the analysis (derived from 1.5 divided by 1.35) to give realistic load effects and then a factor of 1.35 should be applied to the induced load effects in order to obtain design values. As the factor on the load effects is also applied to effects derived from the permanent surcharge, it is necessary to reduce the factor on permanent actions to 1.0 (1.35/1.35).This approach has been adopted here and is consistent with the guidance in the Eurocodes where factors may be applied to actions or effects.

5-5 Design Assumptions

5-5-1 Pile Installation Technique

Tubular piles are to be installed by the Gyropress Method that utilises rotary jack-in system with cutting bits attached on pile toe. It is assumed that ground disturbance is limited to the wall-soil interface and the properties of soil around the tubular piles are unchanged.

5-5-2 Formation Level

The formation level is at 0.0m AOD, i.e. 7.0m below the top of the RC upper wall / ground surface level.

The depth of unplanned excavation for ULS calculations has been taken as 0.5m as recommended by BS EN 1997-1.

5-5-3 Surcharge Load

The geotechnical design of the retaining wall included surcharge loads of 5 kN/m² within 2m from the centre line of the upper wall and 20 kN/m² on the verge and carriageway, i.e. outside the 2m-wide area from the upper wall, based on Appendix A of BD 37/01 (Design Manual for Roads and Bridges).

5-5-4 Impact Load

A single horizontal impact force of 500 kN has been assumed to apply uniformly over a length of 3m along the line of parapet, based on BS 6779-1 and Appendix A of BD 37/01. The mean impact force at the top of the RC upper wall has been calculated to be 167 kN/m-run.

5-5-5 Serviceability

The allowable horizontal deflection of the cantilevered retaining walls has been aimed at 1% of the retained height, i.e. 70mm.

It should be noted that installation tolerances of the plan position and vertically of the steel sheet piles need to be added to the calculated deflection in accordance to BS EN 12063 (see Table 6).

Type of wall	Situation during execution	Plan position of pile top (mm)	Verticality[2)] measured over the top 1m % All directions
Sheet pile[4)]	On land over water	≤ 75[1)] ≤ 100[1)]	≤ 1[3)] ≤ 1.5[3)]
Primary element of combined wall		Depending on soil conditions and on length, shape, size and number of secondary elements, these values should be established in each case in order to ensure that de-clutching is not likely occur	
1) Perpendicular to the wall. 2) Where the design requires piles to be driven at an inclination, the tolerances specified in the table are with respect to that direction. 3) May amount to 2% in difficult soils, provided that no strict criteria regarding for example water tightness are specified and de-clutching is not considered to become a problem after excavation. 4) Excluding straight web piles. NOTE : The tolerances regarding the position and the verticality may be additive.			

Table 6. Tolerances of plan position and vertically of the steel sheet piles after installation(after BS EN 12063)

5-5-6 Pile Section Properties

The pile section properties comprise the elastic modulus of steel or concrete, E, and the pile's second moment of area, I (moment of inertia), of the section.

1) Steel tubular pile
From the pile properties table, provided in Chapter 3, the moment of inertia for the steel tubular piles of 1000mm external diameter with the wall thickness of 14mm at 2.5m centres, I_{stp} is 210,846 cm^4/m.

The steel grade and elastic modulus of the steel piles have been assigned to be S 390 GP and 210 GPa, respectively.

2) RC upper wall
The moment of inertia of the RC upper wall, I_{uw}, has been calculated as follows:

$$I_{uw} = d\,b^3 / 12 / d = 1.0\,(1.167)^3 / 12 / 1.0 = 13.244 \times 10^6\ [cm^4/m]$$

where, b : breadth (in-plane) of upper wall
d : unit width (out-of-plane) of upper wall

The concrete grade has been assigned to be mix strength of C35/45 N/mm². The elastic moduli of the concrete have been assumed to be 35 and 17.5 GPa for short-term and long-term, respectively.

5-5-7 Wall Friction Angle and Adhesion Factor

Based on BS EN 1997-1, the wall friction angle "δ" and adhesion factor "α" between the soil and the wall has been assumed as presented in Table 7.

	Wall friction angle, δ		Wall adhesion factor, α
	Steel tubular piles	RC upper wall	
Granular soil	⅔ ϕ'_{peak}	⅔ ϕ'_{peak}	N/A
Cohesive soil	½ ϕ'_{peak}	½ ϕ'_{peak}	ignored

Table 7. Wall friction and adhesion factors used for the retaining wall analysis (after BS EN 1997-1)

5-5-8 Design Life and Durability

The design is required to take into account all foreseeable events that would adversely affect the stability of the retaining structure. Based on Corrosion Rates in Soil, with or without groundwater, a corrosion rate of 1.2mm over the design life of one hundred years has been adopted for the steel piles in undisturbed natural soils. A check on durability of the steel piles with reduced thickness has been undertaken.

5-6 Assumed Construction Sequence

Sequencing of construction activities will be crucial to ensure that failures do not occur during construction. Careful consideration will also need to be given to measures required to achieve ground movement control behind the retaining walls. The following sequence is envisaged for the design option and has been used in analyses.

1) Install steel tubular piles to existing ground level.
2) Expose pile heads and lay blinding concrete.
3) Construct RC upper wall using formwork or precast.
4) Place backfill at the back of the upper wall and compact.
5) Apply surcharge loads on the active side of the wall to represent surfacing and live load.
6) Apply water pressure (worst credible case for ULS or moderately conservative case for SLS).
7) Reduce ground level on the passive side by 0.5m to represent unplanned excavation for ULS case only.
8) Change geotechnical properties of cohesive soil from "undrained" to "drained" conditions to represent the long-term soil conditions.
9) Change elastic modulus of concrete from short-term value to long-term value to represent the effect of creep.
10) Apply an impact load to the top of RC upper wall.

5-7 Results

5-7-1 Tubular King Pile Foundation

1) Summary of Results

Results of WALLAP runs and design summary of retaining wall calculations for the Tubular King Pile Foundation with the toe level of the steel tubular piles at -14.0m AOD are provided in Appendix A. The bending moments and shear forces obtained from the WALLAP analyses without or with the impact load are summarised in Table 8 and 9.

Analysis case (EC7)	Wall stability	Calculated max. bending moment		Calculated max. shear force		Load factor (EC7)	Design bending moment	Design shear force	Max. wall top movement
	[FoS]	[kNm/m]	Elev. [mAOD]	[kN/m]	Elev. [mAOD]		[kNm/m]	[kN/m]	[mm]
SLS	1.55	456	-2.40	110	-8.40	1.35	616	149	**65**
ULS - Comb.1	-	591	-3.60	212	-1.45	1.35	**798**	**286**	-
ULS - Comb.2	**1.06**	1142	-6.10	211	-1.45	1.00	1142	211	-

Table 8. Summary of results from WALLAP analysis without impact load

Analysis case (EC7)	Wall stability	Calculated max. bending moment		Calculated max. shear force		Load factor (EC7)	Design bending moment	Design shear force	Max. wall top movement
	[FoS]	[kNm/m]	Elev. [mAOD]	[kN/m]	Elev. [mAOD]		[kNm/m]	[kN/m]	[mm]
SLS	1.27	1989	-3.60	400	-6.10	1.35	2685	540	**345**
ULS - Comb.1	-	2590	-4.30	434	-9.60	1.35	**3497**	**586**	-
ULS - Comb.2	**0.83**	4296	-8.40	414	-1.45	1.00	4296	414	-

Table 9. Summary of results from WALLAP analysis with impact load

2) Wall Stability

BS EN 1997-1 requires embedded walls to be designed with sufficient embedment length that satisfies vertical, horizontal and moment equilibrium, i.e. a factor of safety above unity is sufficient. Based on the Design Approach 1 - ULS Combination 2 analysis, using factored surcharge loading, factored soil properties and an additional overdig allowance, the stability of the Tubular King Pile Foundation has been determined as a minimum factor of safety = 1.06 and 0.83 for the cases without and with impact load, respectively, as presented in Tables 8 and 9.

Sensitivity analyses indicated that the pile toe level needs to be at least 5m deeper to maintain the global stability of the foundation under the impact load.

3) Structural Forces (WALLAP)

The wall's cross section must be verified against structural failure. Based on the Design Approach 1 - ULS Combination 1 analysis (WALLAP), using unfactored soil strength, factored surcharge loadings and an additional overdig allowance, the design bending moment and shear force have been determined as 798 kNm/m and 286 kN/m, respectively, for the case without the impact load as presented in Table 8. Under the impact load these design bending moment and shear force increased to 3497 kNm/m and 586 kN/m, respectively.

From the wall properties table provided in Chapter 3, the value of the section modulus for the steel tubular pile "D1000-14 @ 2500" is given as S_{stp} = 4217 [cm³/m].

The minimum required section modulus for the tubular piles can be calculated as follows:

- without impact load

  S_{req} = M_d / f_y
  = 798·10³ / 390 = 2046 [cm³/m]
  where, S_{req} : the minimum required section modulus
  M_d : design bending moment
  f_y : yield stress of the steel pile = 390 N/mm²

  → Degree of utilisation = 2046 / 4217 = 48.5% (OK!)

- with impact load

  S_{req} = M_d / f_y
  = 3497·10³ / 390 = 8967 [cm³/m]

  → Degree of utilisation = 8967 / 4217 = 212.6% (to be revised!)

The results indicate that the tubular pile section studied would fail in bending under the impact load.

4) Structural Forces (PLAXIS)

The Plaxis analysis allows to calculate structural forces of individual members from the Tubular King Pile Foundation separately, i.e. steel tubular piles and RC upper wall, based on unfactored soil strength and action.

It should be noted that the effect of the impact load on the retaining structure has not been modelled in 2D FE analysis since the type of load is transient.

Output plots from the Plaxis 2D FE analysis without the impact load are provided in Appendix B as summarised in Table 10.

Figure ref.	Plaxis Output Plots
Figure B.1	Connectivity plot
Figure B.2	Total vertical displacements (Short-term)
Figure B.3	Total vertical displacements (Long-term)
Figure B.4	Total horizontal displacements (Short-term)
Figure B.5	Total horizontal displacements (Long-term)
Figure B.6	Profile of ground surface settlement behind the wall (Short-term)
Figure B.7	Profile of ground surface settlement behind the wall (Long-term)
Figure B.8	Deformed mesh |u| (Long-term)
Figure B.9	Vector of total displacements (Long-term)
Figure B.10	Total shear strain, γ_s (Long-term)
Figure B.11	Distribution of plastic points (Long-term)
Figure B.12	Profile of horizontal wall displacements (Long-term)
Figure B.13	Profile of wall bending moment for CHS D1000-14 (Long-term)
Figure B.14	Profile of wall bending moment for RC upper wall (Long-term)

Figure B.15	Profile of wall shear force for CHS D1000-14 (Long-term)
Figure B.16	Profile of wall shear force for RC upper wall (Long-term)

Table 10. Summary of output plots from Plaxis 2D FE analysis for Tubular King Pile Foundation

By comparing the profiles of structural forces for the steel tubular pile (Figures B.13 and B.15) and the RC upper wall (Figures B.14 and B.16), it can be seen that the steel tubular pile is carrying the larger magnitude of bending moment while similar magnitude of shear force is calculated for both members.

The maximum bending moment (431 kNm/m) is recorded at the upper portion of the steel tubular piles (at -2.50m AOD) and reduced to 231 kNm/m at the base of the RC upper wall before becoming zero at top of the upper wall.

Both the bending moment (BM) and the shear force (SF) calculated by Plaxis are comparable to those calculated by WALLAP SLS analysis (i.e. BM = 456 kNm/m and SF = 110 kN/m).

5) RC Upper Wall

Based on the Design Approach 1 - ULS Combination 1 analysis (WALLAP), the design bending moment and shear force have been calculated as 341 kNm/m and 140 kN/m, respectively.

The reinforcement steel to resist bending moments and shear forces induced in the upper wall has been determined as follows:

- T32 vertical bars at 150mm centres; and
- T25 horizontal bars at 150mm centres.

6) Durability

Based on the corrosion rate of 1.2mm over the design life of one hundred years, the reduced section modulus for the steel tubular pile "D1000-14 @ 2500" can be calculated as follows:

$S_{red} = \pi (d_o^4 - d_i^4) / 32 / d_o / s$

$= \pi [(1000 - 1.2 \times 2)^4 - (972 + 1.2 \times 2)^4] / 32 / (1000 - 1.2 \times 2) / \cdot 10^3 / 2.5 = 3502$ [cm³/m]

where, S_{red} : the reduced section modulus due to corrosion

d_o : external diameter of tubular pile [mm]

d_i : internal diameter of tubular pile [mm]

s : tubular pile spacing [m]

A check on durability of the steel piles can be undertaken by calculating the degree of utilisation for the minimum required section modulus, S_{req}, against the reduced section modulus, S_{red}, as shown below.

- Degree of utilisation without impact load

$= S_{req} / S_{red} = 2046 / 3502 = 58.4\%$ (OK!)

7) Serviceability

The maximum wall top deflection by the WALLAP SLS analysis was calculated as 65mm at the long-term case without the impact load as presented in Table 8. Conversely, based on the Plaxis 2D FE analysis under the same loading conditions, the wall movement was calculated to be 80mm as shown in Figure B.12 (Appendix B). The difference in wall movement between these calculations is due to the effect of consolidation that has explicitly been modelled by Plaxis software.

The predicted ground movements by Plaxis are presented in Figures B.2 to B.9 (Appendix B). The settlements at immediately back of the upper wall are 70mm and 84mm for short-term and long-term cases, respectively, reducing almost linearly to 5mm at 15m away from the wall.

Figures B.10 and B.11 show the development of the active wedge from the surface point at 5m away from the wall down to the formation level.

8) Vehicle Restraint Barrier

As presented above, the Tubular King Pile Foundation system studied is likely to suffer geotechnical and structural failure when the impact load is applied at the top of the RC upper wall. It is, therefore, recommended to specify an appropriate "Working Width" (i.e. width of the restraint system + its maximum dynamic lateral deflection + vehicle intrusion beyond the restraint system "overhang" after BS EN 1317-2) between the vehicle restraint barrier and the RC upper wall.

If there is a requirement to install vehicle restraint barrier on or adjacent to the RC upper wall due to constraint on available land/space and etc., it may be possible to do so by increasing tubular pile sections and reducing the pile spacing.

9) Pedestrian Protection at Retaining Walls

Pedestrians are not normally expected to be present near retaining walls on motorways. However, drivers and passengers of broken down or damaged vehicles, maintenance staff, emergency service personnel and others may need to walk near them and there is a potential danger of persons falling from the top the wall, particularly in poor visibility or adverse weather conditions [after TD 19/06 (Design Manual for Roads and Bridges)]. Hence, it is recommended to erect pedestrian restraint system, e.g. handrail, along the top of the RC upper wall.

5-8 Summary

A summary of design of the Tubular King Pile Foundation is presented in Table 11 and Figure 6.

Wall type	Material	Pile section / Wall width	Pile / Wall length [m]	Pile / Wall top elevation [m AOD]	Reinforcement
Tubular pile	Steel S 390 GP	D1000-14 @ 2500mm c/c	14.0	7.0	-
RC wall	Concrete C 35/45	Top: 500mm Base: 1167mm	7.0	0.0	T32 vertical bars @ 150 c/c T25 horizontal bars @ 150 c/c

Table 11. Summary of design of Tubular King Pile Foundation

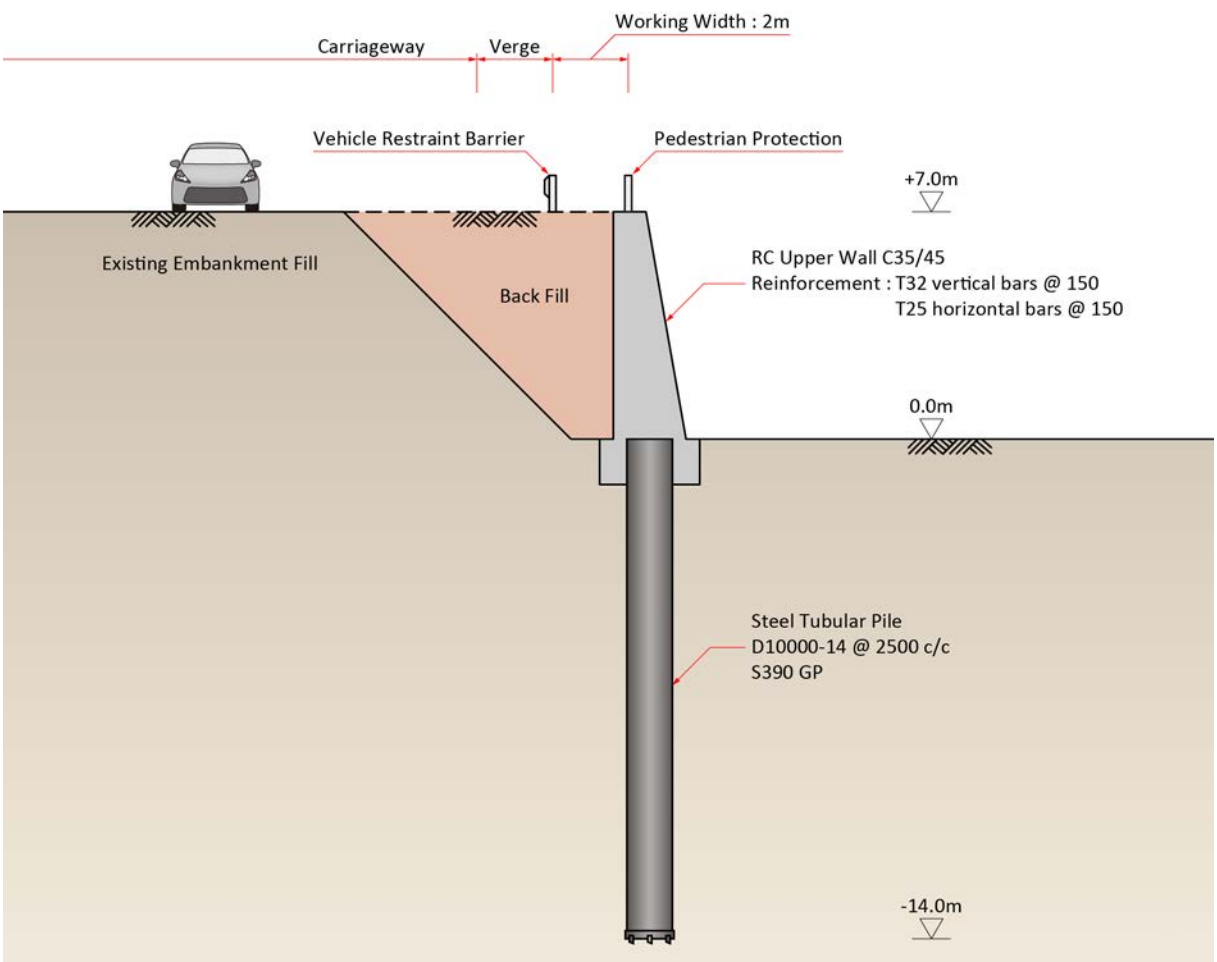


Figure 6. Section showing design of the Tubular King Pile Foundation

APPENDICES

APPENDIX A
Design of Tubular King Pile Foundation based on WALLAP

APPENDIX B
Plaxis 2D FE Analysis of Tubular King Pile Foundation

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