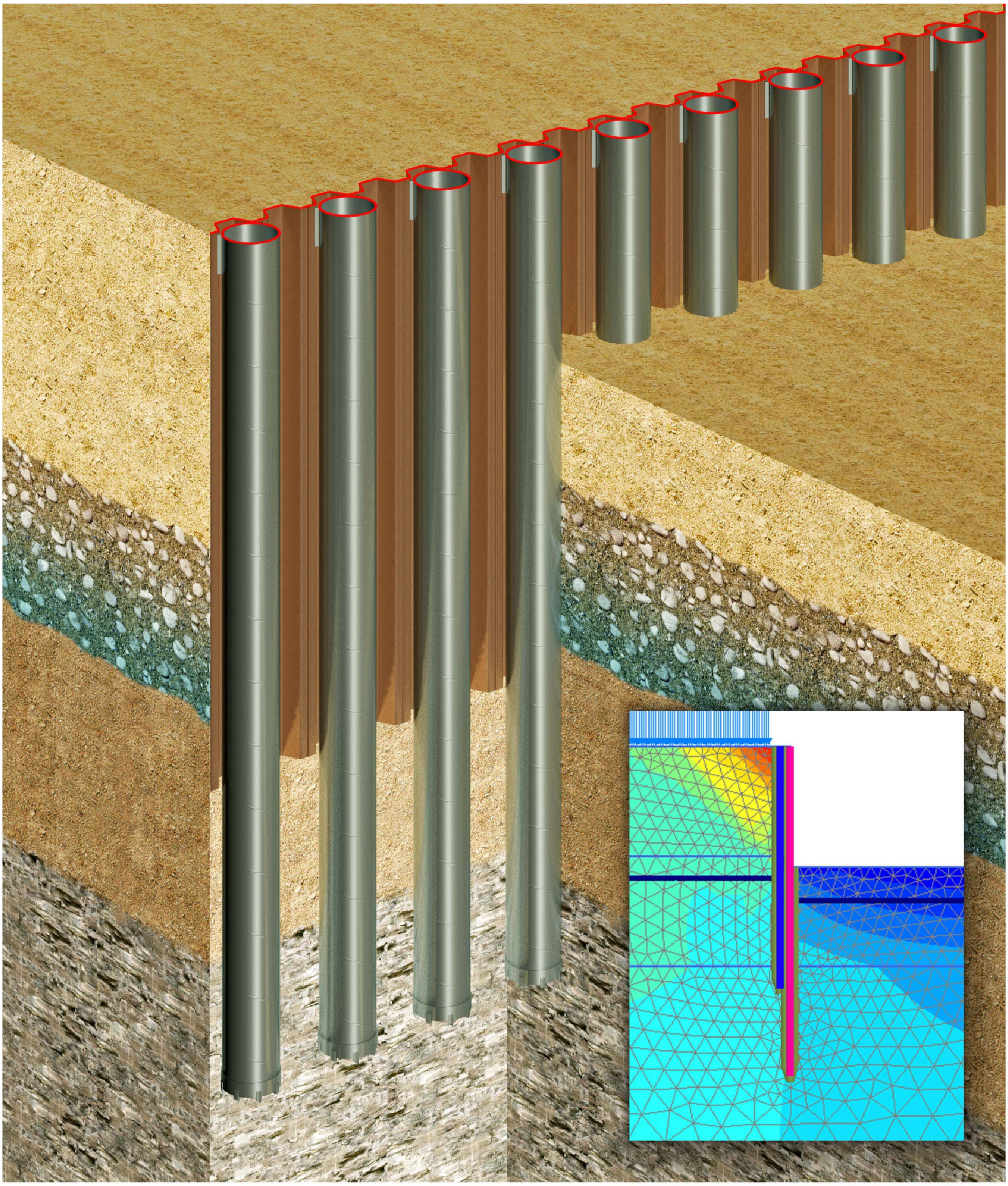
COMBI-GYRO WALL SYSTEM

- High Modulus Steel Combined Wall -

Ver. Tube / Hat Wall Vol.1 Design



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Chapter 1 Introduction

The purpose of this document is to provide model practice guidelines for the design of the Combi-Gyro Wall to be installed by 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 Combi-Gyro Wall are efficiency of physical wall properties and reusability. The Combi-Gyro Wall comprises steel tubular piles as the primary elements and steel sheet piles as the secondary elements. The efficiencies of physical wall 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 Wall Configuration

Combi-Gyro Wall System is a combined wall with great bending stiffness, which incorporates the following elements and acts as a "built-up beam structure".

1. **Steel Tubular Piles**: Primary elements (High modulus main structural elements)
   Tubular piles resist lateral load when used as a retaining wall or cofferdam, and vertical loads when used as bearing piles.
2. **Steel Sheet Piles**: Intermediate elements (Soil-retaining and load-transferring elements)
   Sheet piles transfer soil and hydrostatic pressure to the tubular piles.

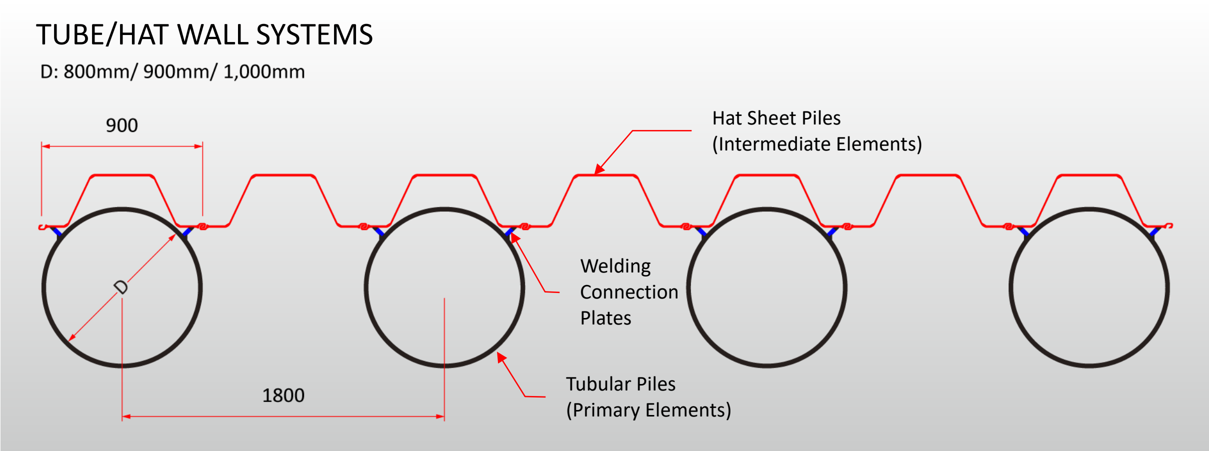

Figure 1. Wall Configuration

Chapter 3 Wall Properties

The primary piles of the Combi-Gyro Wall System are installed to a depth necessary to achieve the required passive toe resistance while steel sheet piles can be supplied in shorter lengths to act simply as a barrier for the soil or groundwater. These shorter sheets result in an overall reduction in piles required as well as less installation time.

After primary piles and intermediate piles are installed, they are jointed together with welding connections to achieve effective horizontal load transfer.

The combination of the primary piles and intermediate piles acts as "a built-up beam structure" and combined wall profiles can be calculated as follows:-

3-1 Combined Elastic Section Modulus

Zsys = Zstp + Zssp

Zsys : Elastic Section Modulus of System

Zstp : Elastic Section Modulus of Steel Tubular Piles

Zssp : Elastic Section Modulus of Steel Sheet Piles

3-2 Combined Moment of Inertia

Isys = Istp + Issp

Isys : Moment of Inertia of System

Istp : Moment of Inertia of Steel Tubular Piles

Issp : Moment of Inertia of Steel Sheet Piles

3-3 Denomination of the Combi-Gyro Wall System

D1000 - 18 / 25H

D1000	18	25H
Outside Diameter of Tubular Piles	Thickness of Tubular Piles	Type of Hat Sheet Piles

3-4 Properties of Combi-Gyro Wall

3-4-1 Tube/Hat Wall

Type of System	Steel Tubular Piles									Hat Sheet Piles			System Total		
	Outside Diameter (mm)	Wall thickness (mm)	Inside Diameter (mm)	Spacing (mm)	Section Modulus Z (cm^3)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4)	Moment of Inertia I (cm^4/m)	Mass per m2 of wall (kg/m2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m2 of wall (kg/m2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m2 of wall (kg/m2)
D800-10/10H	800	10	780	1800	4841	2690	193647	107582	108.2	902	10500	96.0	3592	118082	204.2
D800-10/25H	800	10	780	1800	4841	2690	193647	107582	108.2	1610	24400	126.0	4300	131982	234.2
D800-10/45H	800	10	780	1800	4841	2690	193647	107582	108.2	2450	45000	163.0	5140	152582	271.2
D800-10/50H	800	10	780	1800	4841	2690	193647	107582	108.2	2760	51100	186.0	5450	158682	294.2
D800-12/10H	800	12	776	1800	5766	3203	230632	128129	129.6	902	10500	96.0	4105	138629	225.6
D800-12/25H	800	12	776	1800	5766	3203	230632	128129	129.6	1610	24400	126.0	4813	152529	255.6
D800-12/45H	800	12	776	1800	5766	3203	230632	128129	129.6	2450	45000	163.0	5653	173129	292.6
D800-12/50H	800	12	776	1800	5766	3203	230632	128129	129.6	2760	51100	186.0	5963	179229	315.6
D800-14/10H	800	14	772	1800	6676	3709	267050	148361	150.8	902	10500	96.0	4611	158861	246.8
D800-14/25H	800	14	772	1800	6676	3709	267050	148361	150.8	1610	24400	126.0	5319	172761	276.8
D800-14/45H	800	14	772	1800	6676	3709	267050	148361	150.8	2450	45000	163.0	6159	193361	313.8
D800-14/50H	800	14	772	1800	6676	3709	267050	148361	150.8	2760	51100	186.0	6469	199461	336.8
D800-16/10H	800	16	768	1800	7573	4207	302907	168282	171.9	902	10500	96.0	5109	178782	267.9
D800-16/25H	800	16	768	1800	7573	4207	302907	168282	171.9	1610	24400	126.0	5817	192682	297.9
D800-16/45H	800	16	768	1800	7573	4207	302907	168282	171.9	2450	45000	163.0	6657	213282	334.9
D800-16/50H	800	16	768	1800	7573	4207	302907	168282	171.9	2760	51100	186.0	6967	219382	357.9
D900-12/10H	900	12	876	1800	7334	4074	330034	183352	146.0	902	10500	96.0	4976	193852	242.0
D900-12/25H	900	12	876	1800	7334	4074	330034	183352	146.0	1610	24400	126.0	5684	207752	272.0
D900-12/45H	900	12	876	1800	7334	4074	330034	183352	146.0	2450	45000	163.0	6524	228352	309.0
D900-12/50H	900	12	876	1800	7334	4074	330034	183352	146.0	2760	51100	186.0	6834	234452	332.0
D900-14/10H	900	14	872	1800	8499	4722	382470	212483	169.9	902	10500	96.0	5624	222983	265.9
D900-14/25H	900	14	872	1800	8499	4722	382470	212483	169.9	1610	24400	126.0	6332	236883	295.9
D900-14/45H	900	14	872	1800	8499	4722	382470	212483	169.9	2450	45000	163.0	7172	257483	332.9
D900-14/50H	900	14	872	1800	8499	4722	382470	212483	169.9	2760	51100	186.0	7482	263583	355.9
D900-16/10H	900	16	868	1800	9649	5360	434189	241216	193.8	902	10500	96.0	6262	251716	289.8
D900-16/25H	900	16	868	1800	9649	5360	434189	241216	193.8	1610	24400	126.0	6970	265616	319.8
D900-16/45H	900	16	868	1800	9649	5360	434189	241216	193.8	2450	45000	163.0	7810	286216	356.8
D900-16/50H	900	16	868	1800	9649	5360	434189	241216	193.8	2760	51100	186.0	8120	292316	379.8
D900-18/10H	900	18	864	1800	10782	5990	485198	269554	217.5	902	10500	96.0	6892	280054	313.5
D900-18/25H	900	18	864	1800	10782	5990	485198	269554	217.5	1610	24400	126.0	7600	293954	343.5
D900-18/45H	900	18	864	1800	10782	5990	485198	269554	217.5	2450	45000	163.0	8440	314554	380.5
D900-18/50H	900	18	864	1800	10782	5990	485198	269554	217.5	2760	51100	186.0	8750	320654	403.5
D1000-12/10H	1000	12	976	1800	9091	5050	454544	252525	162.4	902	10500	96.0	5952	263025	258.4
D1000-12/25H	1000	12	976	1800	9091	5050	454544	252525	162.4	1610	24400	126.0	6660	276925	288.4
D1000-12/45H	1000	12	976	1800	9091	5050	454544	252525	162.4	2450	45000	163.0	7500	297525	325.4
D1000-12/50H	1000	12	976	1800	9091	5050	454544	252525	162.4	2760	51100	186.0	7810	303625	348.4
D1000-14/10H	1000	14	972	1800	10542	5857	527116	292842	189.1	902	10500	96.0	6759	303342	285.1
D1000-14/25H	1000	14	972	1800	10542	5857	527116	292842	189.1	1610	24400	126.0	7467	317242	315.1
D1000-14/45H	1000	14	972	1800	10542	5857	527116	292842	189.1	2450	45000	163.0	8307	337842	352.1
D1000-14/50H	1000	14	972	1800	10542	5857	527116	292842	189.1	2760	51100	186.0	8617	343942	375.1
D1000-16/10H	1000	16	968	1800	11976	6653	598797	332665	215.7	902	10500	96.0	7555	343165	311.7
D1000-16/25H	1000	16	968	1800	11976	6653	598797	332665	215.7	1610	24400	126.0	8263	357065	341.7
D1000-16/45H	1000	16	968	1800	11976	6653	598797	332665	215.7	2450	45000	163.0	9103	377665	378.7
D1000-16/50H	1000	16	968	1800	11976	6653	598797	332665	215.7	2760	51100	186.0	9413	383765	401.7
D1000-18/10H	1000	18	964	1800	13392	7440	669596	371998	242.2	902	10500	96.0	8342	382498	338.2
D1000-18/25H	1000	18	964	1800	13392	7440	669596	371998	242.2	1610	24400	126.0	9050	396398	368.2
D1000-18/45H	1000	18	964	1800	13392	7440	669596	371998	242.2	2450	45000	163.0	9890	416998	405.2
D1000-18/50H	1000	18	964	1800	13392	7440	669596	371998	242.2	2760	51100	186.0	10200	423098	428.2
D1000-20/10H	1000	20	960	1800	14790	8217	739518	410844	268.5	902	10500	96.0	9119	421344	364.5
D1000-20/25H	1000	20	960	1800	14790	8217	739518	410844	268.5	1610	24400	126.0	9827	435244	394.5
D1000-20/45H	1000	20	960	1800	14790	8217	739518	410844	268.5	2450	45000	163.0	10667	455844	431.5
D1000-20/50H	1000	20	960	1800	14790	8217	739518	410844	268.5	2760	51100	186.0	10977	461944	454.5
D1000-22/10H	1000	22	956	1800	16171	8984	808572	449207	294.8	902	10500	96.0	9886	459707	390.8
D1000-22/25H	1000	22	956	1800	16171	8984	808572	449207	294.8	1610	24400	126.0	10594	473607	420.8
D1000-22/45H	1000	22	956	1800	16171	8984	808572	449207	294.8	2450	45000	163.0	11434	494207	457.8
D1000-22/50H	1000	22	956	1800	16171	8984	808572	449207	294.8	2760	51100	186.0	11744	500307	480.8

Table1. Tube /Hat Wall Properties

Chapter 4 Retaining Wall Design

4-1 General

The orientation of the Combi-Gyro Wall is determined depending on the purpose of the wall. For normal retaining wall purpose, tubular piles are located at the passive side as described in "Orientation Pattern A" below.
In the case of Orientation Pattern A, the depth of the sheet pile wall can be minimised as the sheet piles lean against the tubular piles. The depth is determined by taking into consideration the risk of boiling, heaving and slip circle failure.

Orientation Pattern B is opposite to Orientation Pattern A, i.e. sheet piles are at passive side as described below. Combi-Gyro Wall in Orientation Pattern B can be selected when a smoother wall surface is required. Also, as the tubular piles are not exposed, structural degradation due to corrosion can be minimised.

4-1-1 Orientation Pattern A : Tubular Piles at Passive Side

Figure 2. Orientation Pattern A

4-1-2 Orientation Pattern B : Sheet Piles at Passive Side

Figure 3. Orientation Pattern B

4-2 Embedded Depth of Combi-Gyro Wall

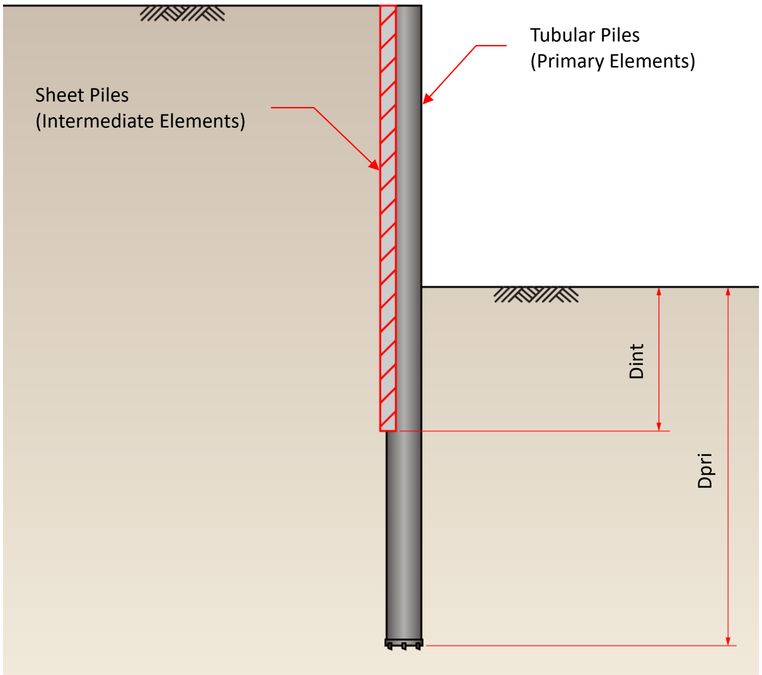

Figure 4. Orientation Pattern A

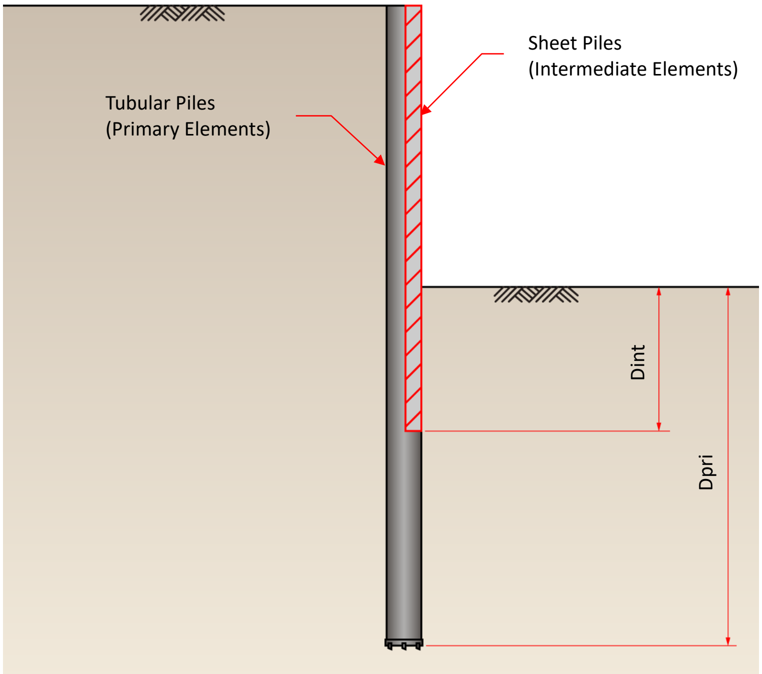

Figure 5. Orientation Pattern B

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

Tubular piles, as the primary elements of a combined wall, act as the retaining elements against the earth and water pressures whilst the secondary elements (intermediate sheet piles) only fill the gap between the primary elements and transmit the loads resulting from earth and water pressures to the primary elements. Thus, the design of the combined wall can be undertaken as a continuous retaining wall.

Limit equilibrium methods are commonly 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;
- retained height; and
- propped or cantilevered.

4-2-2 Embedded Depth of Sheet Piles D_{int}

Orientation Pattern A

In theory the intermediate sheet piles are only required from pile head level to the depth where the net earth pressure becomes zero (see the schematic earth pressure diagram shown in Figure 6). In practice the design embedded depth D_{int} is extended below the zero earth pressure level by one to two metres for safety reasons. Besides, careful consideration should be given to avoid underflow in the case of high differential water pressure, or where there is a danger of scour.

Orientation Pattern B

The first step is to neglect the presence of the primary tubular piles and to assume all the earth and water pressures to be resisted by the intermediate sheet piles, thus, the design embedded depth D_{int} is equal to D_{pri}.

Secondary, performance of the complex wall structure system needs to be assessed by the soil/structure interaction analysis using the finite element (FE) method. By modelling the wall elements explicitly, e.g. tubular pile, sheet pile and connection plate, structural forces in each element and the serviceability, i.e. wall deflection, can be quantified. Based on outcome of the FE analysis together with assessment of underflow and etc., D_{int} can be determined.

In addition the driveability and bending capacity of the sheet piles should also be checked.

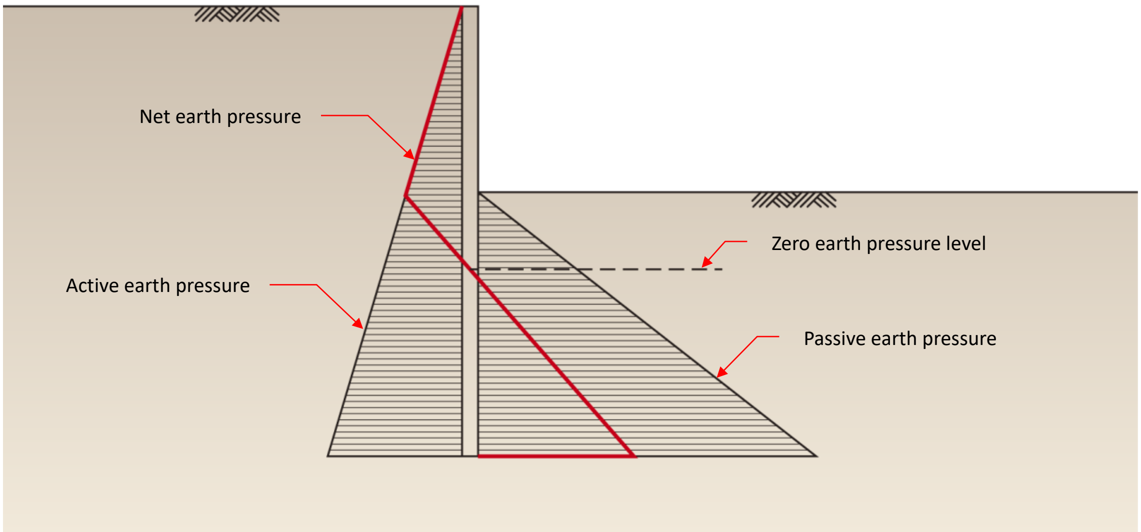

Figure6. Schematic earth pressure diagram

4-3 Passive Mobilisation Mechanism

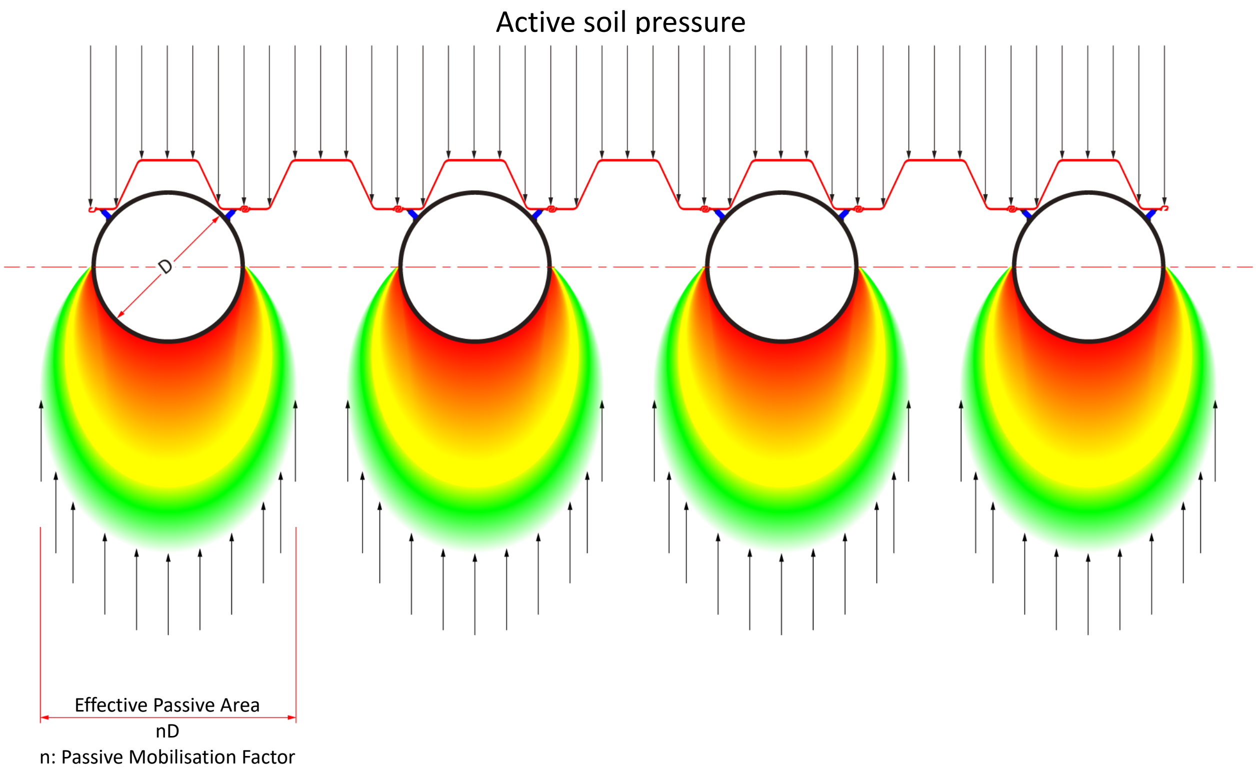

Figure 7. Schematic effective area for passive soil pressure

When the tubular pile is 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 8, is useful to visualise the pressure developed in the effective passive area.

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.

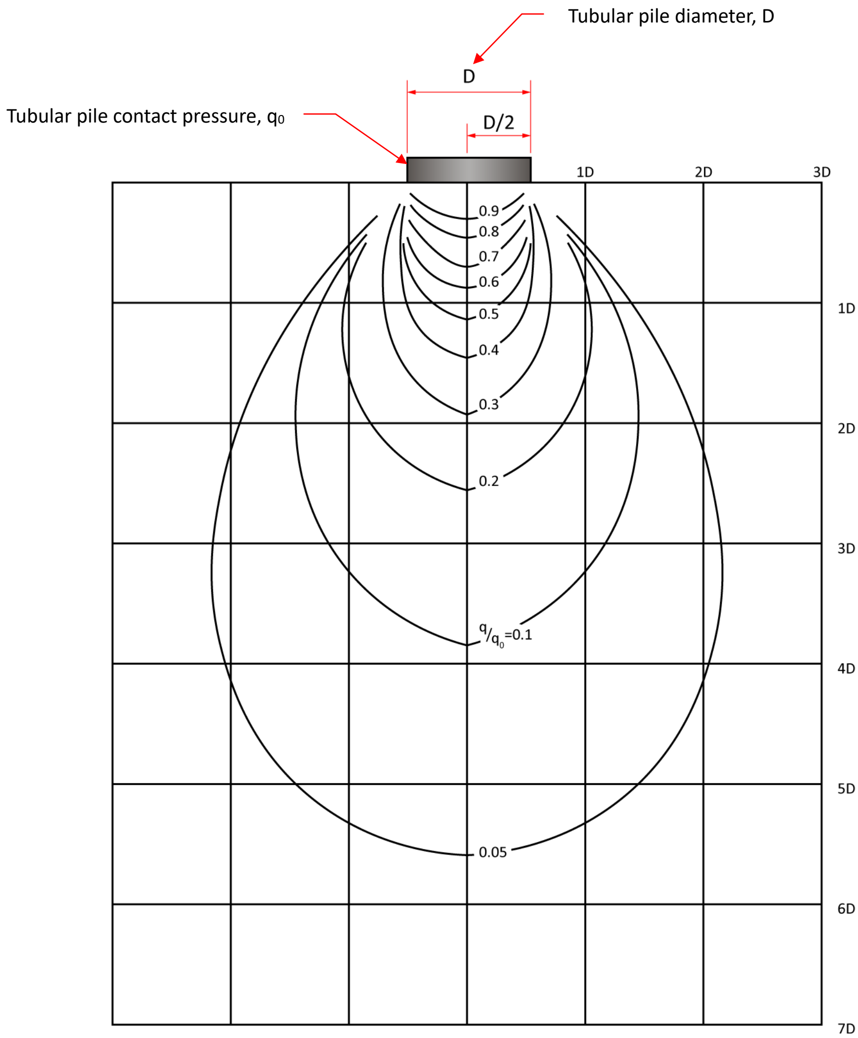

Figure 8. Pressure bulbs formed on the passive side of a tubular pile, showing the intensity of pressure q/q0,based on the Boussinesq equation (after Bowles [1996])

The effective passive area (nD) at the distance H and the angle θ can be obtained from the schematic relationship shown in Figure 8 for a given intensity of the pressure, q/q0.

Earth pressure distributions acting on the Combi-Gyro Wall is rather complex as presented in Figures 9 and 10 for the orientation patterns A and B, respectively.

At the depths above formation level the earth pressure only acts at the back of the wall without any reaction force acting in front of the wall. Hence, all the lateral pressure is transferred to the wall below the formation level.

At the depths between the formation level and sheet pile toe level the resultant force of the lateral pressure transferred from the above formation level and the active earth pressure at these depths is resisted by the passive earth pressure.

Finally, at the depths below the sheet pile toe level the active earth pressure is applied to tubular piles only. The lateral force transferred from the wall above the sheet pile toe level also acts on the piles. These forces are resisted by the passive pressure developed in the effective passive zone.

4-3-1 Orientation Pattern A

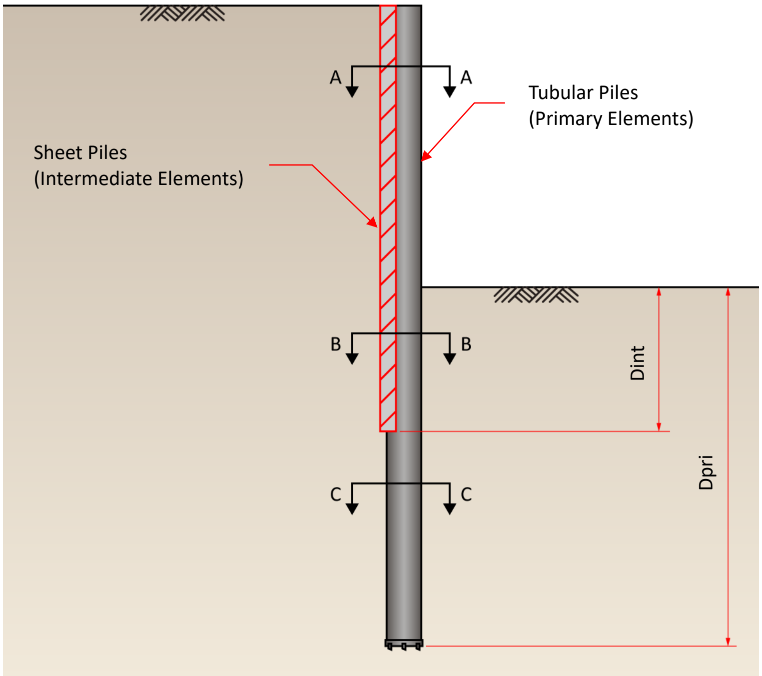

Figure 9(a). Combi-Gyro Wall - Section (Pattern A)

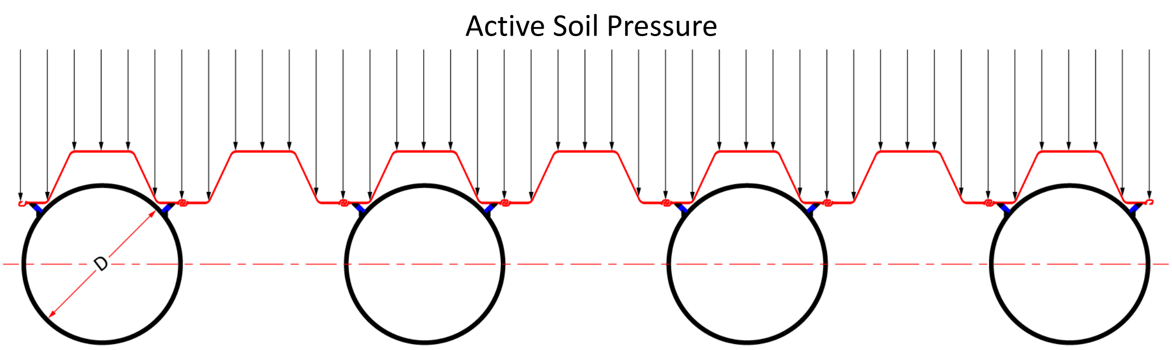

Figure 9(b). Earth pressure diagram - Plan in section A-A (Pattern A, above formation level)

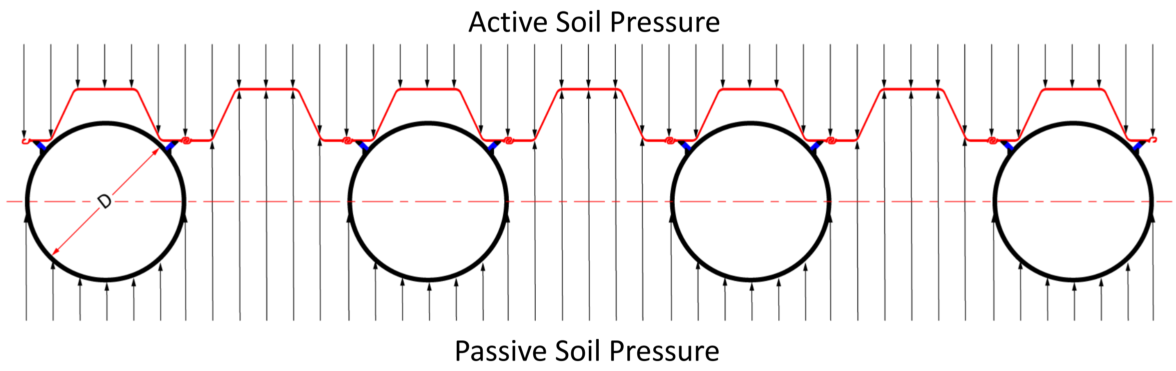

Figure 9(c). Earth pressure diagram - Plan in section B-B (Pattern A, above SSP toe level)

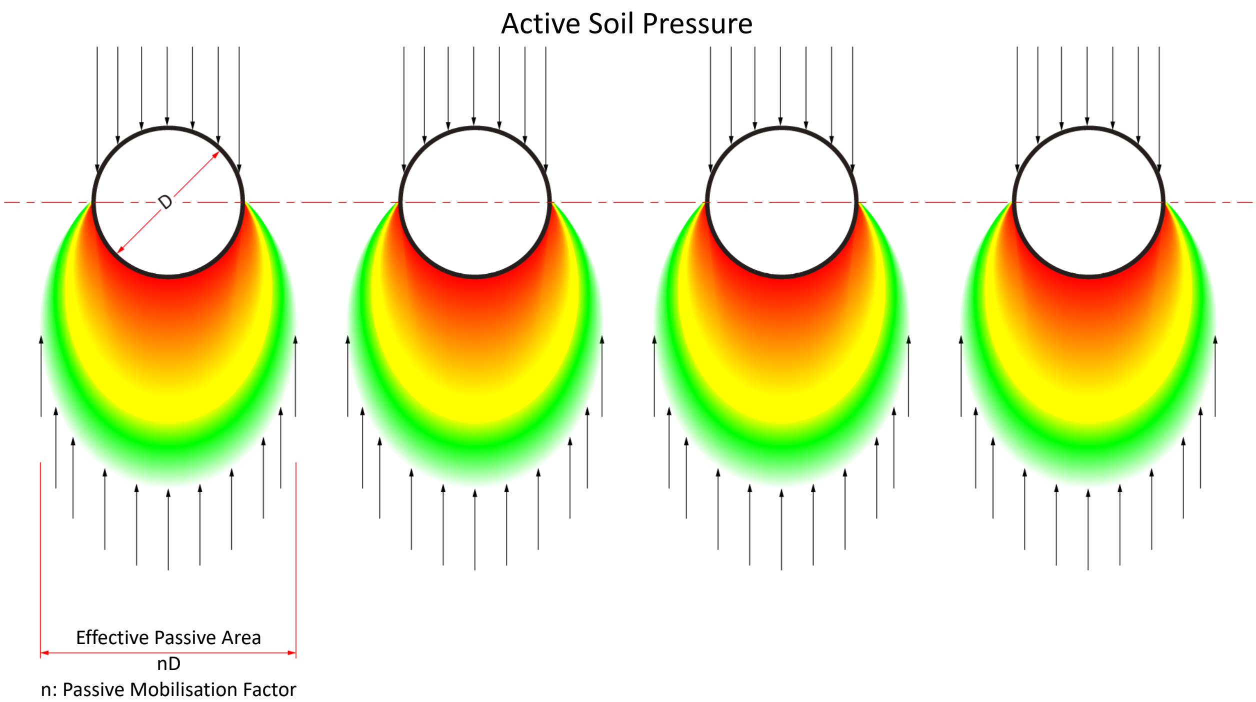

Figure 9(d). Earth pressure diagram - Plan in section C-C (Pattern A, below SSP toe level)

4-3-2 Orientation Pattern B

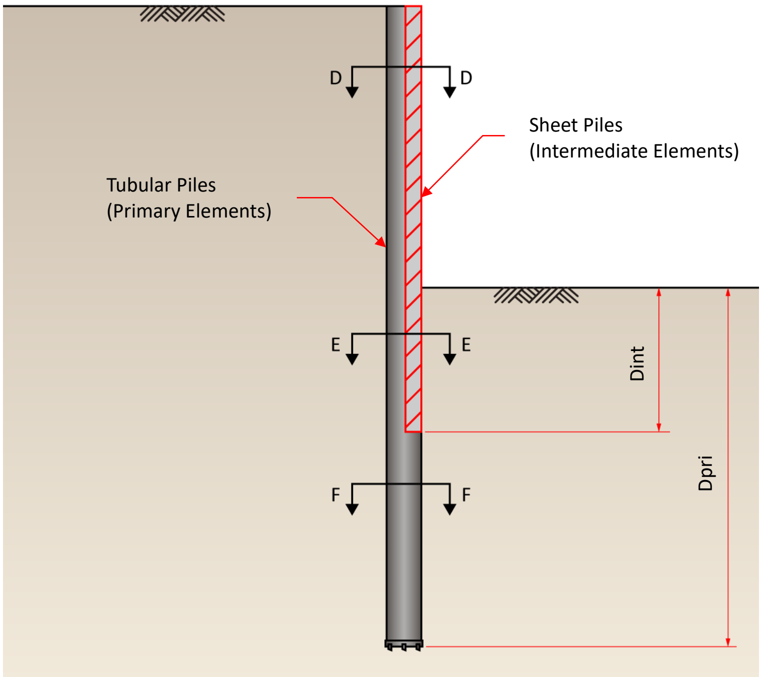

Figure 10(a). Combi-Gyro Wall - Section (Pattern B)

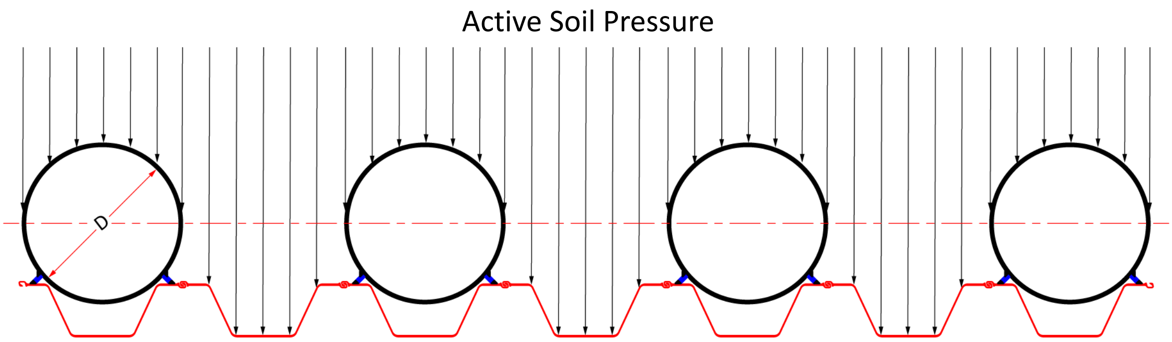

Figure 10(b). Earth pressure diagram - Plan in section D-D (Pattern B, above formation level)

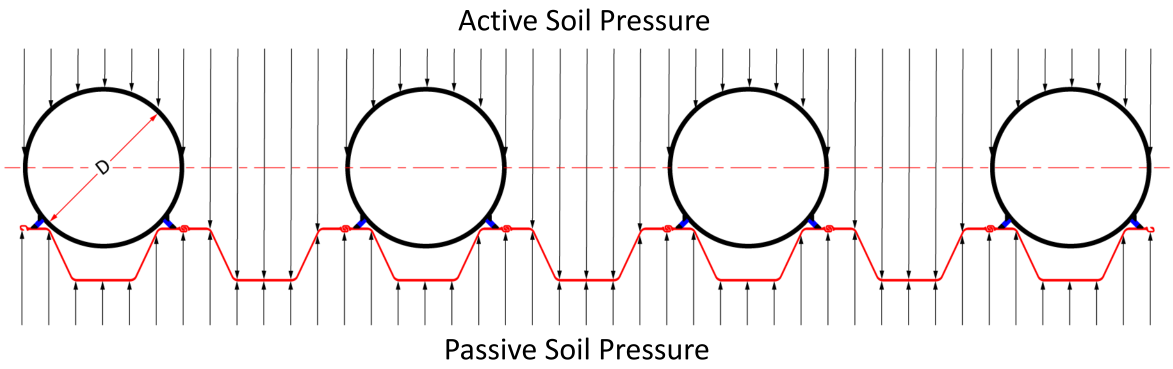

Figure 10(c). Earth pressure diagram - Plan in section E-E (Pattern B, above SSP toe level)

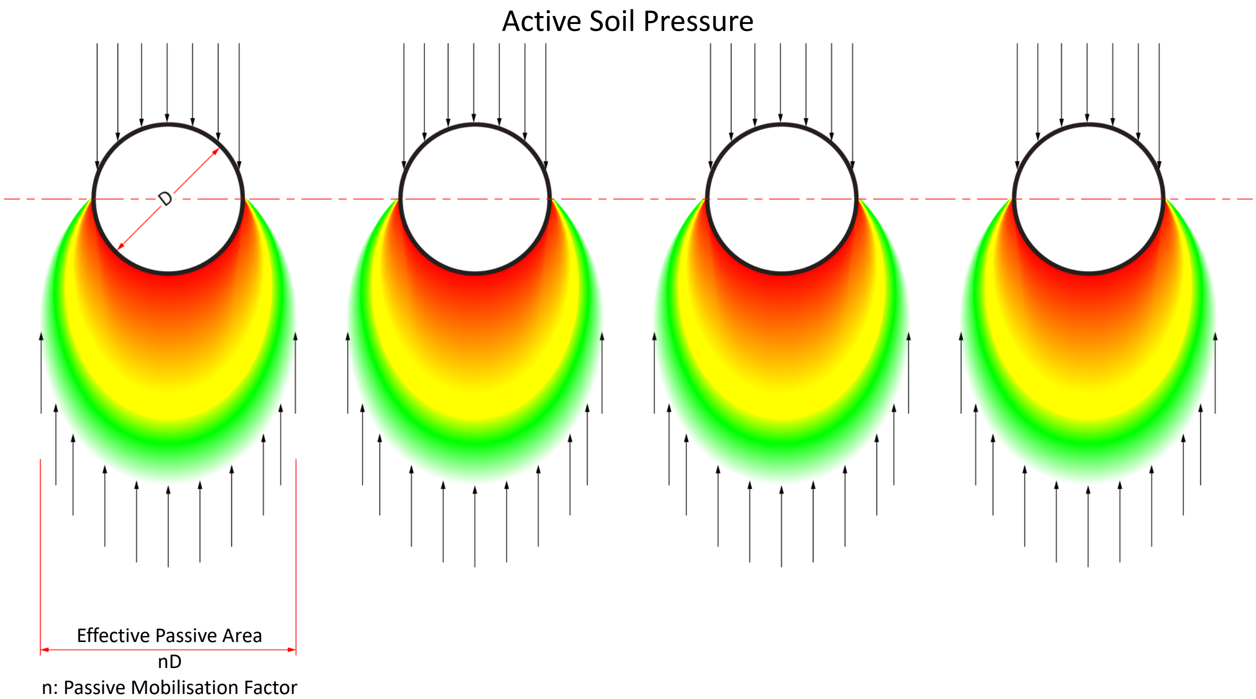

Figure 10(d). Earth pressure diagram - Plan in section F-F (Pattern B, below SSP toe level)

4-4 Durability

The effective life of unpainted or otherwise unprotected Combi-Gyro Wall, depends upon the combined effects of imposed stresses and corrosion.

Performance is clearly optimised where low corrosion rates exist at primary elements (tubular piles) side and/ or positions of high imposed stresses.

Eurocode 3: part 5 consider the end of the effective life of steel sheet 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 opposite faces of a Combi-Gyro Wall may be exposed to different combinations of environments. The following tables indicate 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 and sheet 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.

4-4-2 Loss of thickness (mm) per face due to corrosion of steel tubular and sheet piles in fresh water or seawater

Environments	5 years	25years	50years	75years	100years	125years
Common fresh water (river, ship canal…) in the zone of high attack(water line)	0.15	0.55	0.90	1.15	1.40	1.65
Very polluted fresh water (sewage, industrial effluent…) in the zone of high attack (water line)	0.30	1.30	2.30	3.30	4.30	5.30
Sea water in temperate climate in the zone of high attack (low water and splash zones)	0.55	1.90	3.75	5.60	7.50	Protection system required
Sea water in temperate climate in the zone of permanent immersion or in the intertidal zone	0.25	0.90	1.75	2.60	3.50	4.40

Table 3. Corrosion Rates in Fresh Water or in Sea Water

Note1; The highest corrosion rate is usually found in the splash zone or at the low water level in tidal waters. However, in most cases, the highest bending stresses occur in the permanent immersion zone.

Note2; The values given for 5 years and 25 years are based on measurements, whereas the other values are extrapolated.

Note3; The values in this table for corrosion loss in the low water zone apply to situations where the effects of Accelerated Low Water Corrosion (ALWC) are not a design requirement. ALWC is a particularly aggressive form of corrosion associated with bacterial activity at low water level in marine conditions. Attack is random both within and between locations and typically at or just above the lowest astronomical tide (LAT) level. Due to the high rate of steel loss when ALWC occurs, the life expectancy of a pile will be short and it is recommended that a protection system is used to control the situation rather than reliance on sacrificial steel. Suitable options may be painting or cementitious coating but it is also recommended that consideration is given to installation of a cathodic protection system either immediately or at a later date if necessary. Whilst this phenomenon might not affect every location, if ignored, this rapid form of attack can result in costly repair and maintenance works at an unexpectedly early stage in the life of a structure.

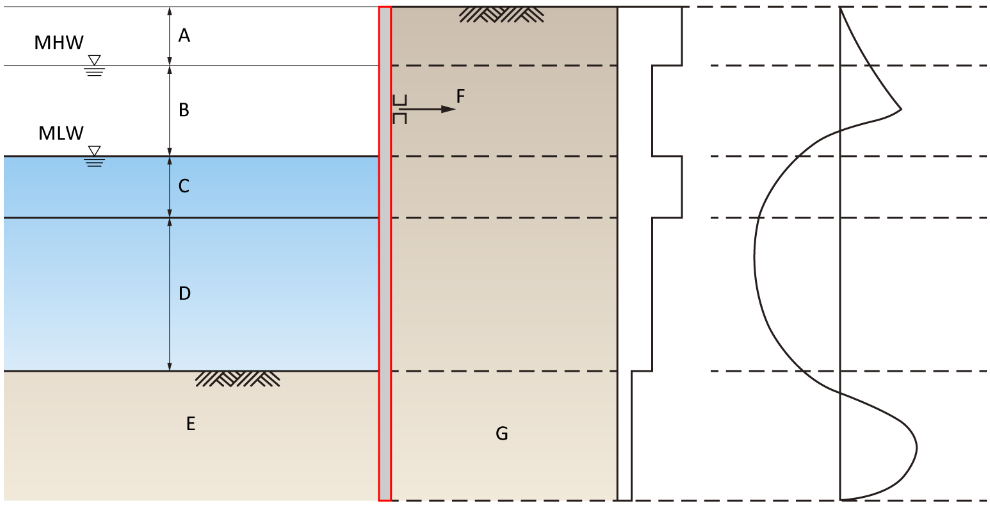

Figure 11. Corrosion Rate Distribution

4-4-3 Combi-Gyro Wall orientation for waterfront structures

Where Combi-Gyro Wall is constructed as a permanent waterfront structure, especially in marine environments, the wall orientation is a critical issue to optimise performance and effective life of the Combi-Gyro Wall.

As the primary elements (tubular piles) resist a majority portion of the bending moment, they are normally located at soil side so that the corrosion rate on the primary elements is minimised.

In the case of Combi-Gyro Wall, the primary elements can entirely be protected from high corrosion aggressiveness by the continuous intermediate elements (sheet piles).

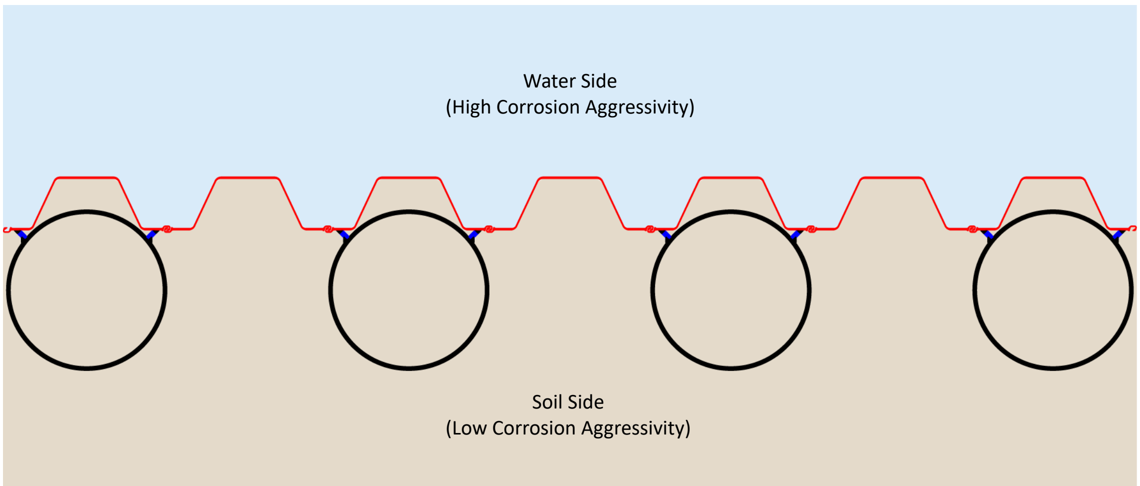

Figure 12. Wall Orientation for Waterfront Structure

Chapter 5 Design Case Study

5-1 Introduction

These calculations detail the design of a cantilevered Combi-Gyro Wall (Tube/Hat, Pattern A) forming 5.5m-deep excavation as a temporary retaining structure with a design life of five years, located at a typical site in central London. The wall comprises steel tubular piles of 900mm external diameter (with the wall thickness of 16mm) aligned at 1.8m centres and continuous Hat 25H steel sheet piles at the back of the tubular piles.

The Geosolve WALLAP software has been used to analyse the retaining wall in accordance with BS EN 1997-1 (2004), 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 finite element software package "Plaxis". The Plaxis analysis also enabled to calculate wall deflections and structural forces of individual members from the Combi-Gyro Wall separately, i.e. primary steel tubular piles and intermediate steel sheet piles.

Once the design of the Combi-Gyro Wall (Tube/Hat, Pattern A) was completed, a cantilevered Secant Piled Wall that could have the similar serviceability to the Combi-Gyro Wall was determined through a series of sensitivity analyses based on the WALLAP software.

Results of the designs for the cantilevered Combi-Gyro Wall (Tube/Hat, Pattern A) and Secant Piled Wall will be presented and compared in this report.

5-2 List of Design Standards and References

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5-3 Ground Conditions

5-3-1 Ground Model

Typical ground conditions seen in central London have been adopted for the analyses with the following geological formations:

a) Made Ground

The Made Ground generally comprises clayey to gravelly sand or soft to firm sandy gravelly clay with varying amounts of rubble, concrete and brick. The material has been assumed as a medium dense granular soil.

b) Terrace Gravel

The Terrace Gravel is generally described as medium dense, angular to sub-rounded, sandy, fine to coarse gravel of flint.

c) London Clay

The London Clay was deposited in a deep marine environment and is relatively homogeneous in lithology in comparison to the underlying Lambeth Group. The material is typically described as stiff closely fissured silty clay with K_0 values ranging from 1.5 to 2.5 due to its heavily overconsolidated nature. The thickness of the formation in central London ranges from 20m to 60m..

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

Made Ground:	+10.0m AOD to +5.0m AOD
Terrace Gravel:	+5.0m AOD to 0.0m AOD
London Clay:	0.0m AOD to -20.0m AOD

5-3-2 Geotechnical Design Parameters

The geotechnical design parameters for each of the formation have been derived, based on general knowledge and HGC's experience in working on the London geology.

A summary of the geotechnical parameters used for the retaining wall analysis is presented in Table 4.

Strata	Elevation (top of strata mAOD)	Thickness (m)	Unit weight (kN/m³)	Angle of Shearing resistance ϕ'_{peak} (Deg.)	Effective cohesion (kN/m²)	Undrained shear strength (kN/m²)	Drained Stiffness E' (MN/m²)	Undrained Stiffness Eu (MN/m²)	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.)
Made Ground	10.0	5.0	18	30	0	-	15	-	0.30	-	0.50	10^{-5}	0
River Terrace Deposits	5.0	5.0	19	35	0	-	50	-	0.30	-	0.43	10^{-5}	5
London Clay	0.0	40.0	20	20	10	100 + 7z	80 + 5.6z	100 + 7z	0.20	0.49	1.50	10^{-10}	12.5

Table 4. Summary of geotechnical parameters for the retaining wall analysis

<u>Notes on design geotechnical parameters</u>

1) Values of the unit weight, Poisson's ratio and permeability are based on general knowledge and HGC's experience in working on London geology.
2) For cohesive soils the Poisson's ratio of $\nu_u = 0.49$ assigned since $\nu_u = 0.50$ would results in an infinite value of bulk modulus in Plaxis analysis (after Plaxis b.v. [2015]).
3) For granular soils the angle of shearing resistance ϕ'_{peak} derived from correlation with typical SPT-N values (after Peck et al. [1974]).
4) For granular soils the stiffness E' derived from correlation with typical SPT-N values using E'/N = 1.0 for Made Ground and E'/N = 2.0 for Terrace Gravel (after Stroud [1989]).
5) Values of K_0 for granular soils derived from the relationship $K_0 = 1 - \sin \phi'_{peak}$.
6) For granular soils the angle of dilatancy ψ derived from the relationship $\psi = \phi - 30°$ (after Plaxis b.v. [2015])
7) London Clay Formation assumed to be "Divisions B/C".
8) For London Clay c' and ϕ'_{peak} based on published data and HGC's experience in working on London geology.
9) For London Clay c_u, where z is the depth below top of London Clay stratum, based on published data and HGC's experience in working on London geology.
10) For London Clay the undrained stiffness E_u derived from correlation using $E_u = 1000c_u$ (after Jardine et al. [1984]).
11) For London Clay the drained stiffness E' derived using the relationship $E' = E_u (1+\nu') / (1+\nu_u)$.
12) Permeability and the value of K_0 for London Clay chosen based on published data (after Hight et al. [2003]).
13) London Clay ψ for drained analysis chosen based on published data and ψ = 0 adopted for undrained analysis.

5-3-3 Design Groundwater Levels

Typical groundwater regime in central London consists of a perched water table within the Terrace Gravel (the upper aquifer) and a deep water table in the lower aquifer above Chalk, e.g. within the London Clay, Lambeth Group and Thanet Sand.

The groundwater table for the design life of next five years has been assumed at +3.0m AOD. During an extreme flooding event the groundwater table at the site might rise to above ground level. In such events the structural integrity of the proposed temporary retaining wall might be compromised.

In order to address the risk of the extreme flooding events an observational method approach is envisaged by means of a number of stand pipe piezometers for the entire duration of the construction works. Thus, the following design groundwater levels have been used for the design of the retaining walls as presented in Table 5.

Design case	Active side [mAOD]	Passive side [mAOD]
Worst credible (ULS)	5.0	3.0
Moderately conservative (SLS)	4.0	3.0

Table 5. Design groundwater levels for the retaining wall analysis

Shall the water table on the active side rise higher than the moderately conservative design level (4.0m AOD), dewatering measure shall be considered. Those might include allowing seepage in the excavation and evacuation of groundwater using sumps, groundwater lowering using relieve well or similar.

5-4 Design Approach

5-4-1 Retaining Wall Analysis

The Geosolve WALLAP software (ver. 6.05) has been used to analyse the retaining walls in accordance with Design Approach 1 in BS EN 1997-1 (2004) 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 a 2D FE software package, Plaxis 2D (ver. 2015.01). 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 enables to calculate wall deflections and structural forces of individual members from the Combi-Gyro Wall separately, i.e. primary steel tubular piles and intermediate steel sheet piles.

5-4-2 Partial Factors

The design uses safety factors obtained from BS EN 1997-1, summarised in Table 6. 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 6. Summary of partial factors used for design of retaining walls (after BS EN 1997-1 [2004])

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

1) Tubular Piles
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.

2) Steel Sheet Piles
Steel sheet piles are to be installed by the Press-in Method. It is assumed that pre-augering may be carried out in the active earth pressure side of sheet pile in-pan areas only.

5-5-2 Formation Level

The formation level is at 4.5m AOD, i.e. 5.5m below the pile head/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 a 10 kN/m² surcharge load on the active side. This surcharge has been applied at 0.5m from the centre line of the retaining wall.

5-5-4 Serviceability

The allowable horizontal deflection of the cantilevered retaining walls has been taken as 26mm.

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 12063:1999 (see Table 7).

<table>
<tr><td rowspan="3">Type of wall</td><td rowspan="3">Situation during execution</td><td rowspan="3">Plan position of pile top (mm)</td><td>Verticality[2] measured over the top 1m</td></tr>
<tr><td>%</td></tr>
<tr><td>All directions</td></tr>
<tr><td>Sheet pile[4]</td><td>On land over water</td><td>≤ 75[1]
≤ 100[1]</td><td>≤ 1[3]
≤ 1.5[3]</td></tr>
<tr><td>Primary element of combined wall</td><td></td><td colspan="2">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</td></tr>
<tr><td colspan="4">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 watertightness 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.</td></tr>
</table>

Table 7. Tolerances of plan position and vertically of the steel sheet piles after installation(after BS EN 12063:1999)

5-5-5 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) Combi-Gyro Wall (Tube/Hat, Pattern A)
The Combi-Gyro Wall (Tube/Hat, Pattern A) analysed in this design exercise is comprised of steel tubular piles of 900mm external diameter at 1.8m centres with the wall thickness of 16mm and "Hat" type steel sheet piles 25H. The theoretical centre lines of the tubular piles and the sheet piles are spaced 475mm apart in the 2D FE model.

From the wall properties table, provided by Giken, values of the moment of inertia for each wall member were determined as follows:

$$I_{sys} = I_{stp} + I_{ssp}$$
$$= 241{,}216 + 24{,}400 = 265{,}616\ [\mathrm{cm^4/m}]$$

where, I_{sys}: moment of inertia of Combi-Gyro Wall system
I_{stp}: moment of inertia of steel tubular piles
I_{ssp}: moment of inertia of steel sheet piles

The moment of inertia of the wall system I_{sys} was assigned from the pile head level to the steel sheet piles' toe level, where it was reduced to I_{stp} for the rest of the steel tubular piles.

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

2) Secant Piled Wall (hard/firm)
A series of sensitivity analyses has been undertaken to determine an arrangement of the cantilevered secant pile wall that had a similar serviceability performance to the Combi-Gyro Wall (D900-16 with Hat 25H) in terms of the maximum wall top deflection (i.e. ≈ 26mm).

Based on the sensitivity analyses, 900mm diameter bored piles (hard/firm) with a male-to-male spacing of 1250mm (275mm overlap of male and female piles, as shown in Figure 13) have been chosen for the retaining wall analysis. The concrete grades have been assumed to be mix strength of C30/37 N/mm² and C8/10 N/mm² for the male (hard) and female (firm) piles, respectively.

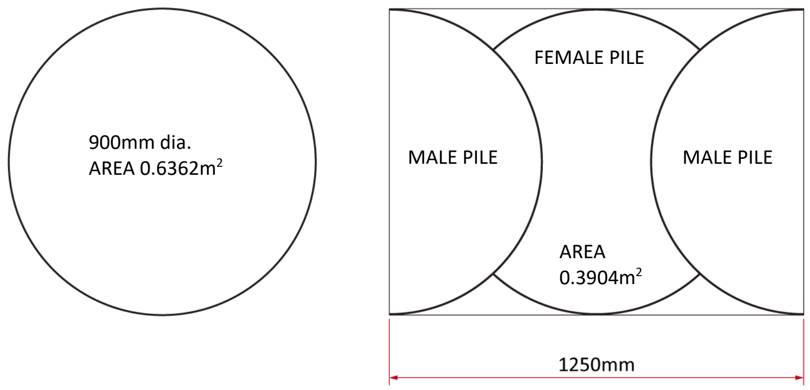

Figure 13. Arrangement of Secant Piled Wall

For calculation of the moment of inertia of the secant piled wall it has been assumed that male piles will act as the primary retaining elements whilst female piles only fill the gap between the male piles and transmit the loads resulting from earth and water pressures to the male piles. Thus, the moment of inertia per metre is determined as:

$I_{spw} = I_{male} / d$
$= \pi r^4 / 4 / d = \pi (0.90/2)^4 / 4 / 1.2 = 2{,}576{,}499$ [cm⁴/m]

where, I_{spw} : moment of inertia of secant piled wall
I_{male} : moment of inertia of male piles
r : male pile radius
d : male pile spacing (centre to centre)

The elastic modulus of the concrete piles has been taken as 19.6 GPa in accordance with guidance in the WALLAP User's Guide, which is 70% of short-term uncracked concrete modulus value (28 GPa).

5-5-6 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 8.

	Wall friction angle, δ		Wall adhesion factor, α
	Steel piles	Concrete piles	
Granular soil	$\frac{2}{3}\ \phi'_{peak}$	ϕ'_{peak}	N/A
Cohesive soil	$\frac{1}{2}\ \phi'_{peak}$	ϕ'_{peak}	ignored

Table 8. Wall friction and adhesion factors used for the retaining wall analysis (after BS EN 1997-1)

5-5-7 Design Life

The design is required to take into account all foreseeable events that would adversely affect the stability of the retaining structure. Since the purpose of the retaining walls is for temporary works, the design life of five years has been adopted and, thus, a check on durability of the steel members has not 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 provided.

1) Install a retaining wall (Combi-Gyro Wall or Secant Piled Wall).
2) Apply surcharge load (UDL 10 kN/m^2) on the active side of the wall.
3) Excavate on the passive side to 4.5m AOD.
4) Apply water pressure (worst credible case for ULS or moderately conservative case for SLS).
5) Change geotechnical properties of London Clay from "undrained" to "drained" conditions to represent the long-term soil conditions (five years after installation of the wall).

5-7 Results

5-7-1 Combi-Gyro Wall (Tube/Hat, Pattern A)

1) Summary of Results

Results of WALLAP runs and design summary of retaining wall calculations for the Combi-Gyro Wall (Tube/Hat, Pattern A) with the toe level of the steel tubular piles at -5.0m AOD are provided in Appendix A. The bending moments and shear forces obtained from the WALLAP analyses are summarised in Table 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	1.64	261	2.30	82	4.50	1.35	352	111	**26**
ULS - Comb.1	-	264	2.30	83	4.50	1.35	**356**	**112**	-
ULS - Comb.2	**1.09**	563	0.80	143	-2.40	1.00	563	143	-

Table 11. Summary of results from WALLAP analysis on the Combi-Gyro Wall (Tube/Hat, Pattern A)

2) Wall Stability

BS EN 1997-1 (2004) 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 loadings, factored soil properties and an additional overdig allowance, the stability of the Combi-Gyro Wall has been determined as a minimum factor of safety = 1.09 as presented in Table 9.

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 design shear force have been determined as 356 kNm/m and 112 kN/m, respectively, as presented in Table 9.

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

$S_{req} = M_d / f_y$

$= 356 \cdot 10^3 / 390 = 914$ [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

From the wall properties table 3-4-1 Tube/Hat Wall, values of the section modulus for the wall system, steel tubular pile and steel sheet pile are given below.

- Section modulus of the Combi-Gyro Wall system: S_{sys} = 6970 [cm³/m] (> 914, OK)
- Section modulus of the steel tubular pile: S_{stp} = 5360 [cm³/m] (> 914, OK)
- Section modulus of the steel sheet pile: S_{ssp} = 1610 [cm³/m] (> 914, OK)

It is clear that the structural integrity of the Combi-Gyro Wall has been verified in all three cases.

4) Structural Forces (PLAXIS)
The Plaxis analysis allows to calculate structural forces of individual members from the Combi-Gyro Wall separately, i.e. steel tubular piles and steel sheet piles, based on unfactored soil strength and action.

Output plots from the Plaxis 2D FE analysis at the final stage, i.e. five years after installation of the wall are provided in Appendix B as summarised in Table 10.

Figure ref.	Plaxis Output Plots
Figure B.1	Connectivity plot
Figure B.2	Deformed mesh $\|u\|$
Figure B.3	Total vertical displacements u_y
Figure B.4	Total horizontal displacements u_x
Figure B.5	Vector of total displacements $\|u\|$
Figure B.6	Total shear strain γ_s
Figure B.7	Distribution of plastic points
Figure B.8	Profile of horizontal wall displacements for CHS D900-16
Figure B.9	Profile of wall bending moment for CHS D900-16
Figure B.10	Profile of wall shear force for CHS D900-16
Figure B.11	Profile of horizontal wall displacements for Hat SSP 25H
Figure B.12	Profile of wall bending moment for Hat SSP 25H
Figure B.13	Profile of wall shear force for Hat SSP 25H

Table 10. Summary of output plots from Plaxis 2D FE analysis forCombi-Gyro Wall (Tube/Hat, Pattern A) provided in Appendix B

By comparing the profiles of wall bending moments for the steel tubular pile (Figure B.9) and the steel sheet pile (Figure B.12), it can be seen that, while the steel tubular pile is carrying the larger magnitude of bending moment (-189.9 kNm/m), the steel sheet pile's contribution to resist the bending moment is relatively small (-17.68 kNm/m). This significant difference in the resistance to the bending moment justifies the design assumption made for the role of the intermediate sheet piles, being a member to transmit the earth and water pressure to the primary tubular piles.

The sum of the bending moments from two wall members calculated by the Plaxis analysis (189.9 + 17.7 ≈ 208 kNm/m) is less than that calculated by the WALLAP SLS analysis (261 kNm/m) as presented in Table 7.1. It should be noted that the magnitude of the bending moment can be reduced if further 2D FE analyses are carried out using stress- and strain-dependant hardening soil constitutive models with small strain stiffness.

5) Intermediate Sheet Piles Toe Level
According to the results from the ULS - Combination 1 analysis, as reported in "Tube-Hat_D900-16-25H_Toe-5mOD_Fmn+4_5mOD_LT_ULS1.rtf" provided in Appendix A, the net pressure becomes zero at an approximate elevation of 4.3m AOD at Stage No. 5. The embedded depth of the intermediate sheet pile is theoretically required down to this elevation. However, due to the fact that a water bearing stratum of Terrace Gravel is present further 4.3m below this level, the design toe level of the sheet piles has been chosen at -1.0m AOD, i.e. 1m into London Clay.

6) Serviceability
The calculated maximum wall top deflection by the WALLAP SLS analysis was recorded as 26mm at the long-term case as presented in Table 9. Based on the Plaxis 2D FE analysis under the same loading conditions, the wall movement was predicted to be 25mm as shown in Figure B.8 (Appendix B).

It should be noted that the magnitude of the wall displacements is highly influenced by soil stiffness values assigned to the FE model. Hence, if further 2D FE analyses are carried out using stress- and strain-dependant hardening soil constitutive models with small strain stiffness, the wall top deflection can be reduced.

The predicted ground settlement, based on the Plaxis output plots presented in Figures B.2 to B.5 (Appendix B), is 21mm at immediately behind the steel sheet piles, reducing almost linearly to 5mm at 5m away from the steel sheet piles.

Figures B.6 and B.7 show the development of the active wedge from the surface point at 5m away from the wall down to the formation level.

5-7-2 Secant Piled Wall

1) Summary of Results
Results of WALLAP runs and design summary of retaining wall calculations for the Secant Piled Wall with the toe level of the male piles at -5.0m AOD are provided in Appendix C. The bending moments and shear forces obtained from the WALLAP analyses are summarised in Table 11.

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	1.72	245	2.30	79	4.50	1.35	331	107	**26**
ULS - Comb.1	-	307	2.30	90	4.00	1.35	**414**	**122**	-
ULS - Comb.2	**1.14**	509	0.80	131	3.50	1.00	509	131	-

Table 11. Summary of results from WALLAP analysis on the Secant Piled Wall

2) Wall Stability
BS EN 1997-1 (2004) 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 loadings, factored soil properties and an additional overdig allowance, the stability of the Secant Piled Wall has been determined as a minimum factor of safety = 1.14 as presented in Table 11.

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 design shear force have been determined as 414 kNm/m and 122 kN/m, respectively, as presented in Table 11. These values are greater than those values for the Combi-Gyro Wall.

The reinforcement steel to resist bending moments and shear forces induced in the secant "male" piles is determined in accordance with BS EN 1992-1-1 and given below.

- Main steel: (8 x B25) x 15m deep
- Shear steel: 600mm OD B12 hoop at 300mm centres

4) Structural Forces (PLAXIS)
The Plaxis analysis also provides calculation of structural forces for the Secant Piled Wall, based on unfactored soil strength and action.

Output plots from the Plaxis 2D FE analysis at the final stage, i.e. five years after installation of the wall are provided in Appendix D as summarised in Table 12.

Figure ref.	Plaxis Output Plots
Figure D.1	Connectivity plot
Figure D.2	Deformed mesh $\|u\|$
Figure D.3	Total vertical displacements u_y
Figure D.4	Total horizontal displacements u_x
Figure D.5	Vector of total displacements $\|u\|$
Figure D.6	Total shear strain γ_s
Figure D.7	Distribution of plastic points
Figure D.8	Profile of horizontal wall displacements for secant piles
Figure D.9	Profile of wall bending moment for secant piles
Figure D.10	Profile of wall shear force for secant piles

Table 12. Summary of output plots from Plaxis 2D FE analysis for Secant Piled Wall provided in Appendix D

The bending moment calculated by the Plaxis analysis (222.8 kNm/m, shown in Figure D.9) is slightly less than that calculated based on the WALLAP SLS analysis (245 kNm/m) as presented in Table 11.

5) Female Piles Toe Level
According to the results from the ULS - Combination 1 analysis, as reported in "SPW_Dia900mm_1250mmCC_Toe-5mOD_Fmn+4_5mOD_LT_ULS1.rtf" provided in Appendix C, the net pressure becomes zero at an approximate elevation of 3.8m AOD at Stage No. 5. The embedded depth of the female pile is theoretically required down to this elevation. However, due to the fact that a water bearing stratum of Terrace Gravel is present further 3.8m below this level, similarly to the design of the intermediate sheet piles for the Combi-Gyro Wall, the design toe level of the female piles has been chosen at -1.0m AOD, i.e. 1m into London Clay.

6) Serviceability
The calculated maximum wall top deflection by the WALLAP SLS analysis was recorded as 26mm at the long-term case as presented in Table 11. Based on the Plaxis 2D FE analysis under the same loading conditions, the wall movement was predicted to be 28mm as shown in Figure D.8 (Appendix D).

As described in Section 5-7-1 6), the use of advanced soil constitutive models in the FE analyses could reduce the wall top deflection.

The predicted ground settlement, based on the Plaxis output plots presented in Figures D.2 to D.5 (Appendix D), is 23mm at immediately back of the secant piles, reducing almost linearly to 5mm at 5m away from the secant piles.

Figures D.6 and D.7 show a similar trend of development of the active wedge behind the secant piles but exhibit less plastic points, compared to those calculated for the Combi-Gyro Wall.

5-8 Summary

The designs of the Combi-Gyro Wall and the Secant Piled Wall are compared in Table 13.

Wall type	Pile material	Pile section	Pile length [m]	Pile spacing [m]	Pile reinforcement	Wall stability (ULS-C2) [FoS]	Design bending moment (ULS-C1) [kNm/m]	Design shear force (ULS-C1) [kN/m]	Max. wall top movement (SLS) [mm]
Combi-Gyro Wall	Steel S 390 GP	D900-16	15.0	1.8	-	1.09	356	112	26
	Steel S 390 GP	Hat 25H	11.0	0.9	-				
Secant Piled Wall	Concrete C 30/37	900mm dia. (male)	15.0	1.25	(8 x B25) x 15m 600mm OD B12 hoop at 300mm c/c	1.14	414	122	26
	Concrete C 8/10	900mm dia. (female)	11.0	1.25	-				

Table 13. Summary of results for Combi-Gyro Wall and Secant Piled Wall from WALLAP analysis

APPENDICES

APPENDIX A
Design of Combi-Gyro Wall based on WALLAP

APPENDIX B
Plaxis 2D FE Analysis of Combi-Gyro Wall

APPENDIX C
Design of Secant Piled Wall based on WALLAP

C-1. Design Summary of SPW (Dia.900mm_1250mmCC).docx

C-2. WALLAP run ID: SPW_Dia900mm_1250mmCC_Toe-5mOD_Fmn+4_5mOD_LT_SLS

C-3. WALLAP run ID: SPW_Dia900mm_1250mmCC_Toe-5mOD_Fmn+4_5mOD_LT_ULS1

C-4. WALLAP run ID: SPW_Dia900mm_1250mmCC_Toe-5mOD_Fmn+4_5mOD_LT_ULS2

APPENDIX D
Plaxis 2D FE Analysis of Secant Piled Wall

Figure D.1	Connectivity plot
Figure D.2	Deformed mesh $\|u\|$
Figure D.3	Total vertical displacements u_y
Figure D.4	Total horizontal displacements u_x
Figure D.5	Vector of total displacements $\|u\|$
Figure D.6	Total shear strain γ_s
Figure D.7	Distribution of plastic points
Figure D.8	Profile of horizontal wall displacements for secant piles (Hard/Firm 900mm dia.@ 1250mm centres)
Figure D.9	Profile of wall bending moment for secant piles (Hard/Firm 900mm dia.@ 1250mm centres)
Figure D.10	Profile of wall shear force for secant piles (Hard/Firm 900mm dia.@ 1250mm centres)

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