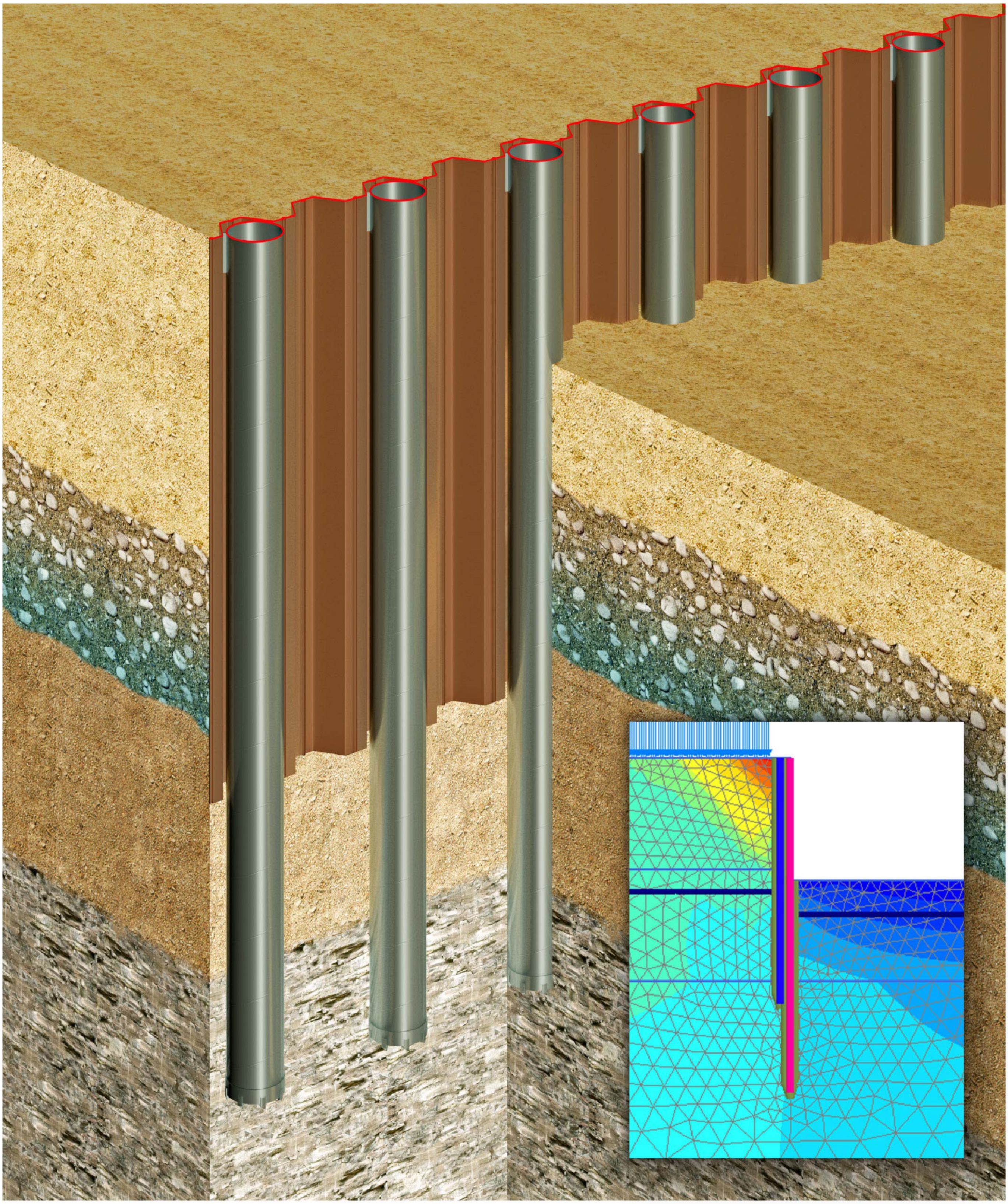
COMBI-GYRO WALL SYSTEM

- High Modulus Steel Combined Wall -

Ver. Tube / Z 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.

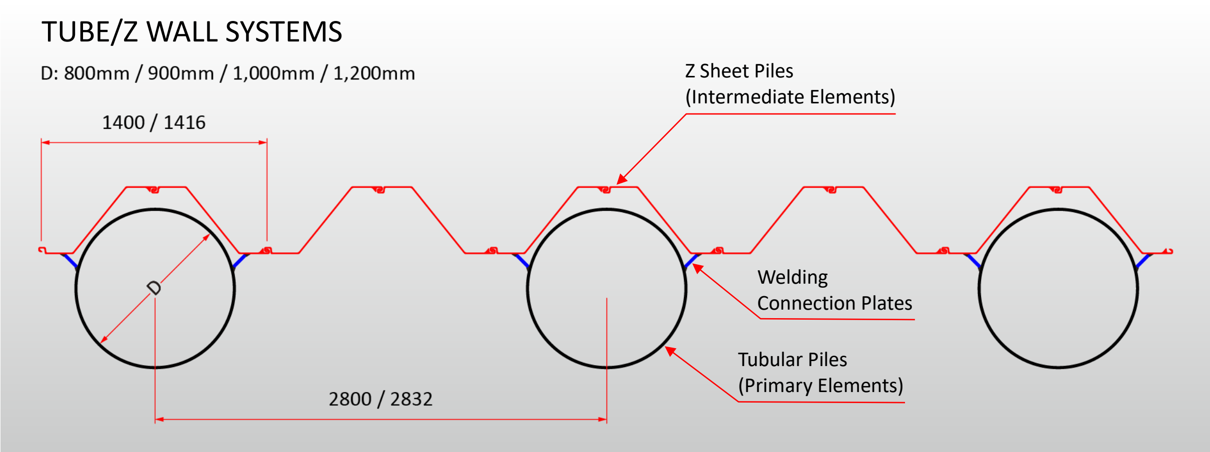


Figure 1. Wall Configuration

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

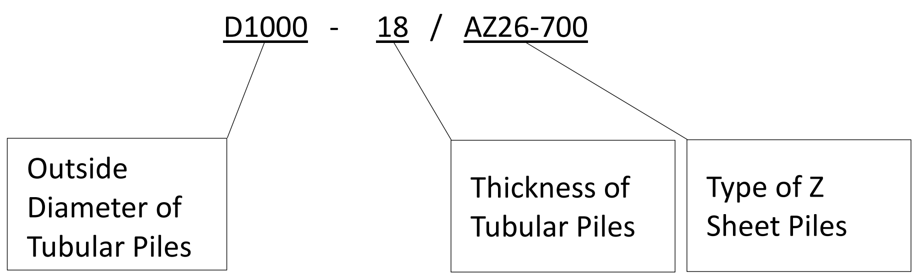
Isys = Istp + Issp

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



3-4 Properties of Combi-Gyro Wall

3-4-1 Tube/Z Wall (AZ Profile)

Type of Wall	Steel Tubular Piles									Z Sheet Piles			Tube/Z Wall 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 m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)
D800-10/AZ20-700	800	10	780	2800	4841	1729	193647	69160	69.6	1945	40960	119.3	3674	110120	188.9
D800-10/AZ24-700N	800	10	780	2800	4841	1729	193647	69160	69.6	2435	55890	128.2	4164	125050	197.8
D800-10/AZ28-700N	800	10	780	2800	4841	1729	193647	69160	69.6	2765	63700	148.7	4494	132860	218.3
D800-10/AZ36-700N	800	10	780	2800	4841	1729	193647	69160	69.6	3590	89610	169.5	5319	158770	239.1
D800-10/AZ40-700N	800	10	780	2800	4841	1729	193647	69160	69.6	3995	100080	191.7	5724	169240	261.3
D800-10/AZ44-700N	800	10	780	2800	4841	1729	193647	69160	69.6	4405	110150	214.2	6134	179310	283.8
D800-10/AZ46-700N	800	10	780	2800	4841	1729	193647	69160	69.6	4605	115370	225.3	6334	184530	294.9
D800-12/AZ20-700	800	12	776	2800	5766	2059	230632	82369	83.3	1945	40960	119.3	4004	123329	202.6
D800-12/AZ24-700N	800	12	776	2800	5766	2059	230632	82369	83.3	2435	55890	128.2	4494	138259	211.5
D800-12/AZ28-700N	800	12	776	2800	5766	2059	230632	82369	83.3	2765	63700	148.7	4824	146069	232.0
D800-12/AZ36-700N	800	12	776	2800	5766	2059	230632	82369	83.3	3590	89610	169.5	5649	171979	252.8
D800-12/AZ40-700N	800	12	776	2800	5766	2059	230632	82369	83.3	3995	100080	191.7	6054	182449	275.0
D800-12/AZ44-700N	800	12	776	2800	5766	2059	230632	82369	83.3	4405	110150	214.2	6464	192519	297.5
D800-12/AZ46-700N	800	12	776	2800	5766	2059	230632	82369	83.3	4605	115370	225.3	6664	197739	308.6
D800-14/AZ20-700	800	14	772	2800	6676	2384	267050	95375	96.9	1945	40960	119.3	4329	136335	216.2
D800-14/AZ24-700N	800	14	772	2800	6676	2384	267050	95375	96.9	2435	55890	128.2	4819	151265	225.1
D800-14/AZ28-700N	800	14	772	2800	6676	2384	267050	95375	96.9	2765	63700	148.7	5149	159075	245.6
D800-14/AZ36-700N	800	14	772	2800	6676	2384	267050	95375	96.9	3590	89610	169.5	5974	184985	266.4
D800-14/AZ40-700N	800	14	772	2800	6676	2384	267050	95375	96.9	3995	100080	191.7	6379	195455	288.6
D800-14/AZ44-700N	800	14	772	2800	6676	2384	267050	95375	96.9	4405	110150	214.2	6789	205525	311.1
D800-14/AZ46-700N	800	14	772	2800	6676	2384	267050	95375	96.9	4605	115370	225.3	6989	210745	322.2
D800-16/AZ20-700	800	16	768	2800	7573	2705	302907	108181	110.5	1945	40960	119.3	4650	149141	229.8
D800-16/AZ24-700N	800	16	768	2800	7573	2705	302907	108181	110.5	2435	55890	128.2	5140	164071	238.7
D800-16/AZ28-700N	800	16	768	2800	7573	2705	302907	108181	110.5	2765	63700	148.7	5470	171881	259.2
D800-16/AZ36-700N	800	16	768	2800	7573	2705	302907	108181	110.5	3590	89610	169.5	6295	197791	280.0
D800-16/AZ40-700N	800	16	768	2800	7573	2705	302907	108181	110.5	3995	100080	191.7	6700	208261	302.2
D800-16/AZ44-700N	800	16	768	2800	7573	2705	302907	108181	110.5	4405	110150	214.2	7110	218331	324.7
D800-16/AZ46-700N	800	16	768	2800	7573	2705	302907	108181	110.5	4605	115370	225.3	7310	223551	335.8
D1000-12/AZ20-700	1000	12	976	2800	9091	3247	454544	162337	104.4	1945	40960	119.3	5192	203297	223.7
D1000-12/AZ24-700N	1000	12	976	2800	9091	3247	454544	162337	104.4	2435	55890	128.2	5682	218227	232.6
D1000-12/AZ28-700N	1000	12	976	2800	9091	3247	454544	162337	104.4	2765	63700	148.7	6012	226037	253.1
D1000-12/AZ36-700N	1000	12	976	2800	9091	3247	454544	162337	104.4	3590	89610	169.5	6837	251947	273.9
D1000-12/AZ40-700N	1000	12	976	2800	9091	3247	454544	162337	104.4	3995	100080	191.7	7242	262417	296.1
D1000-12/AZ44-700N	1000	12	976	2800	9091	3247	454544	162337	104.4	4405	110150	214.2	7652	272487	318.6
D1000-12/AZ46-700N	1000	12	976	2800	9091	3247	454544	162337	104.4	4605	115370	225.3	7852	277707	329.7
D1000-14/AZ20-700	1000	14	972	2800	10542	3765	527116	188256	121.6	1945	40960	119.3	5710	229216	240.9
D1000-14/AZ24-700N	1000	14	972	2800	10542	3765	527116	188256	121.6	2435	55890	128.2	6200	244146	249.8
D1000-14/AZ28-700N	1000	14	972	2800	10542	3765	527116	188256	121.6	2765	63700	148.7	6530	251956	270.3
D1000-14/AZ36-700N	1000	14	972	2800	10542	3765	527116	188256	121.6	3590	89610	169.5	7355	277866	291.1
D1000-14/AZ40-700N	1000	14	972	2800	10542	3765	527116	188256	121.6	3995	100080	191.7	7760	288336	313.3
D1000-14/AZ44-700N	1000	14	972	2800	10542	3765	527116	188256	121.6	4405	110150	214.2	8170	298406	335.8
D1000-14/AZ46-700N	1000	14	972	2800	10542	3765	527116	188256	121.6	4605	115370	225.3	8370	303626	346.9
D1000-16/AZ20-700	1000	16	968	2800	11976	4277	598797	213856	138.7	1945	40960	119.3	6222	254816	258.0
D1000-16/AZ24-700N	1000	16	968	2800	11976	4277	598797	213856	138.7	2435	55890	128.2	6712	269746	266.9
D1000-16/AZ28-700N	1000	16	968	2800	11976	4277	598797	213856	138.7	2765	63700	148.7	7042	277556	287.4
D1000-16/AZ36-700N	1000	16	968	2800	11976	4277	598797	213856	138.7	3590	89610	169.5	7867	303466	308.2
D1000-16/AZ40-700N	1000	16	968	2800	11976	4277	598797	213856	138.7	3995	100080	191.7	8272	313936	330.4
D1000-16/AZ44-700N	1000	16	968	2800	11976	4277	598797	213856	138.7	4405	110150	214.2	8682	324006	352.9
D1000-16/AZ46-700N	1000	16	968	2800	11976	4277	598797	213856	138.7	4605	115370	225.3	8882	329226	364.0
D1000-18/AZ20-700	1000	18	964	2800	13392	4783	669596	239141	155.7	1945	40960	119.3	6728	280101	275.0
D1000-18/AZ24-700N	1000	18	964	2800	13392	4783	669596	239141	155.7	2435	55890	128.2	7218	295031	283.9
D1000-18/AZ28-700N	1000	18	964	2800	13392	4783	669596	239141	155.7	2765	63700	148.7	7548	302841	304.4
D1000-18/AZ36-700N	1000	18	964	2800	13392	4783	669596	239141	155.7	3590	89610	169.5	8373	328751	325.2
D1000-18/AZ40-700N	1000	18	964	2800	13392	4783	669596	239141	155.7	3995	100080	191.7	8778	339221	347.4
D1000-18/AZ44-700N	1000	18	964	2800	13392	4783	669596	239141	155.7	4405	110150	214.2	9188	349291	369.9
D1000-18/AZ46-700N	1000	18	964	2800	13392	4783	669596	239141	155.7	4605	115370	225.3	9388	354511	381.0
D1000-20/AZ20-700	1000	20	960	2800	14790	5282	739518	264114	172.6	1945	40960	119.3	7227	305074	291.9
D1000-20/AZ24-700N	1000	20	960	2800	14790	5282	739518	264114	172.6	2435	55890	128.2	7717	320004	300.8
D1000-20/AZ28-700N	1000	20	960	2800	14790	5282	739518	264114	172.6	2765	63700	148.7	8047	327814	321.3
D1000-20/AZ36-700N	1000	20	960	2800	14790	5282	739518	264114	172.6	3590	89610	169.5	8872	353724	342.1
D1000-20/AZ40-700N	1000	20	960	2800	14790	5282	739518	264114	172.6	3995	100080	191.7	9277	364194	364.3
D1000-20/AZ44-700N	1000	20	960	2800	14790	5282	739518	264114	172.6	4405	110150	214.2	9687	374264	386.8
D1000-20/AZ46-700N	1000	20	960	2800	14790	5282	739518	264114	172.6	4605	115370	225.3	9887	379484	397.9
D1000-22/AZ20-700	1000	22	956	2800	16171	5776	808572	288776	189.5	1945	40960	119.3	7721	329736	308.8
D1000-22/AZ24-700N	1000	22	956	2800	16171	5776	808572	288776	189.5	2435	55890	128.2	8211	344666	317.7
D1000-22/AZ28-700N	1000	22	956	2800	16171	5776	808572	288776	189.5	2765	63700	148.7	8541	352476	338.2
D1000-22/AZ36-700N	1000	22	956	2800	16171	5776	808572	288776	189.5	3590	89610	169.5	9366	378386	359.0
D1000-22/AZ40-700N	1000	22	956	2800	16171	5776	808572	288776	189.5	3995	100080	191.7	9771	388856	381.2
D1000-22/AZ44-700N	1000	22	956	2800	16171	5776	808572	288776	189.5	4405	110150	214.2	10181	398926	403.7
D1000-22/AZ46-700N	1000	22	956	2800	16171	5776	808572	288776	189.5	4605	115370	225.3	10381	404146	414.8

Type of Wall	Steel Tubular Piles									Z Sheet Piles			Tube/Z Wall 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 m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)
D1200-14/AZ20-700	1200	14	1172	2800	15288	5460	917281	327600	146.2	1945	40960	119.3	7405	368560	265.5
D1200-14/AZ24-700N	1200	14	1172	2800	15288	5460	917281	327600	146.2	2435	55890	128.2	7895	383490	274.4
D1200-14/AZ28-700N	1200	14	1172	2800	15288	5460	917281	327600	146.2	2765	63700	148.7	8225	391300	294.9
D1200-14/AZ36-700N	1200	14	1172	2800	15288	5460	917281	327600	146.2	3590	89610	169.5	9050	417210	315.7
D1200-14/AZ40-700N	1200	14	1172	2800	15288	5460	917281	327600	146.2	3995	100080	191.7	9455	427680	337.9
D1200-14/AZ44-700N	1200	14	1172	2800	15288	5460	917281	327600	146.2	4405	110150	214.2	9865	437750	360.4
D1200-14/AZ46-700N	1200	14	1172	2800	15288	5460	917281	327600	146.2	4605	115370	225.3	10065	442970	371.5
D1200-16/AZ20-700	1200	16	1168	2800	17385	6209	1043072	372526	166.9	1945	40960	119.3	8154	413486	286.2
D1200-16/AZ24-700N	1200	16	1168	2800	17385	6209	1043072	372526	166.9	2435	55890	128.2	8644	428416	295.1
D1200-16/AZ28-700N	1200	16	1168	2800	17385	6209	1043072	372526	166.9	2765	63700	148.7	8974	436226	315.6
D1200-16/AZ36-700N	1200	16	1168	2800	17385	6209	1043072	372526	166.9	3590	89610	169.5	9799	462136	336.4
D1200-16/AZ40-700N	1200	16	1168	2800	17385	6209	1043072	372526	166.9	3995	100080	191.7	10204	472606	358.6
D1200-16/AZ44-700N	1200	16	1168	2800	17385	6209	1043072	372526	166.9	4405	110150	214.2	10614	482676	381.1
D1200-16/AZ46-700N	1200	16	1168	2800	17385	6209	1043072	372526	166.9	4605	115370	225.3	10814	487896	392.2
D1200-18/AZ20-700	1200	18	1164	2800	19460	6950	1167577	416992	187.4	1945	40960	119.3	8895	457952	306.7
D1200-18/AZ24-700N	1200	18	1164	2800	19460	6950	1167577	416992	187.4	2435	55890	128.2	9385	472882	315.6
D1200-18/AZ28-700N	1200	18	1164	2800	19460	6950	1167577	416992	187.4	2765	63700	148.7	9715	480692	336.1
D1200-18/AZ36-700N	1200	18	1164	2800	19460	6950	1167577	416992	187.4	3590	89610	169.5	10540	506602	356.9
D1200-18/AZ40-700N	1200	18	1164	2800	19460	6950	1167577	416992	187.4	3995	100080	191.7	10945	517072	379.1
D1200-18/AZ44-700N	1200	18	1164	2800	19460	6950	1167577	416992	187.4	4405	110150	214.2	11355	527142	401.6
D1200-18/AZ46-700N	1200	18	1164	2800	19460	6950	1167577	416992	187.4	4605	115370	225.3	11555	532362	412.7
D1200-20/AZ20-700	1200	20	1160	2800	21513	7683	1290805	461002	207.9	1945	40960	119.3	9628	501962	327.2
D1200-20/AZ24-700N	1200	20	1160	2800	21513	7683	1290805	461002	207.9	2435	55890	128.2	10118	516892	336.1
D1200-20/AZ28-700N	1200	20	1160	2800	21513	7683	1290805	461002	207.9	2765	63700	148.7	10448	524702	356.6
D1200-20/AZ36-700N	1200	20	1160	2800	21513	7683	1290805	461002	207.9	3590	89610	169.5	11273	550612	377.4
D1200-20/AZ40-700N	1200	20	1160	2800	21513	7683	1290805	461002	207.9	3995	100080	191.7	11678	561082	399.6
D1200-20/AZ44-700N	1200	20	1160	2800	21513	7683	1290805	461002	207.9	4405	110150	214.2	12088	571152	422.1
D1200-20/AZ46-700N	1200	20	1160	2800	21513	7683	1290805	461002	207.9	4605	115370	225.3	12288	576372	433.2
D1200-22/AZ20-700	1200	22	1156	2800	23546	8409	1412765	504559	228.3	1945	40960	119.3	10354	545519	347.6
D1200-22/AZ24-700N	1200	22	1156	2800	23546	8409	1412765	504559	228.3	2435	55890	128.2	10844	560449	356.5
D1200-22/AZ28-700N	1200	22	1156	2800	23546	8409	1412765	504559	228.3	2765	63700	148.7	11174	568259	377.0
D1200-22/AZ36-700N	1200	22	1156	2800	23546	8409	1412765	504559	228.3	3590	89610	169.5	11999	594169	397.8
D1200-22/AZ40-700N	1200	22	1156	2800	23546	8409	1412765	504559	228.3	3995	100080	191.7	12404	604639	420.0
D1200-22/AZ44-700N	1200	22	1156	2800	23546	8409	1412765	504559	228.3	4405	110150	214.2	12814	614709	442.5
D1200-22/AZ46-700N	1200	22	1156	2800	23546	8409	1412765	504559	228.3	4605	115370	225.3	13014	619929	453.6
D1200-25/AZ20-700	1200	25	1150	2800	26556	9484	1593346	569052	258.7	1945	40960	119.3	11429	610012	378.0
D1200-25/AZ24-700N	1200	25	1150	2800	26556	9484	1593346	569052	258.7	2435	55890	128.2	11919	624942	386.9
D1200-25/AZ28-700N	1200	25	1150	2800	26556	9484	1593346	569052	258.7	2765	63700	148.7	12249	632752	407.4
D1200-25/AZ36-700N	1200	25	1150	2800	26556	9484	1593346	569052	258.7	3590	89610	169.5	13074	658662	428.2
D1200-25/AZ40-700N	1200	25	1150	2800	26556	9484	1593346	569052	258.7	3995	100080	191.7	13479	669132	450.4
D1200-25/AZ44-700N	1200	25	1150	2800	26556	9484	1593346	569052	258.7	4405	110150	214.2	13889	679202	472.9
D1200-25/AZ46-700N	1200	25	1150	2800	26556	9484	1593346	569052	258.7	4605	115370	225.3	14089	684422	484.0

Table1. Tube /Z Wall (AZ Profile) Properties

3-4-2 Tube/Z Wall (Hoesch Profile)

Type of Wall	Steel Tubular Piles									Z Sheet Piles			Tube/Z Wall 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 m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)
D800-10/2007	800	10	780	2800	4841	1729	193647	69160	69.6	1945	40845	119.4	3674	110005	189.0
D800-10/2407	800	10	780	2800	4841	1729	193647	69160	69.6	2450	53000	136.7	4179	122160	206.3
D800-10/2607	800	10	780	2800	4841	1729	193647	69160	69.6	2600	57200	146.2	4329	126360	215.8
D800-10/2807	800	10	780	2800	4841	1729	193647	69160	69.6	2765	60830	156.7	4494	129990	226.3
D800-10/3607	800	10	780	2800	4841	1729	193647	69160	69.6	3595	89875	167.7	5324	159035	237.3
D800-10/3807	800	10	780	2800	4841	1729	193647	69160	69.6	3800	95000	179.8	5529	164160	249.4
D800-10/4007	800	10	780	2800	4841	1729	193647	69160	69.6	3970	99250	190.0	5699	168410	259.6
D800-12/2007	800	12	776	2800	5766	2059	230632	82369	83.3	1945	40845	119.4	4004	123214	202.7
D800-12/2407	800	12	776	2800	5766	2059	230632	82369	83.3	2450	53000	136.7	4509	135369	220.0
D800-12/2607	800	12	776	2800	5766	2059	230632	82369	83.3	2600	57200	146.2	4659	139569	229.5
D800-12/2807	800	12	776	2800	5766	2059	230632	82369	83.3	2765	60830	156.7	4824	143199	240.0
D800-12/3607	800	12	776	2800	5766	2059	230632	82369	83.3	3595	89875	167.7	5654	172244	251.0
D800-12/3807	800	12	776	2800	5766	2059	230632	82369	83.3	3800	95000	179.8	5859	177369	263.1
D800-12/4007	800	12	776	2800	5766	2059	230632	82369	83.3	3970	99250	190.0	6029	181619	273.3
D800-14/2007	800	14	772	2800	6676	2384	267050	95375	96.9	1945	40845	119.4	4329	136220	216.3
D800-14/2407	800	14	772	2800	6676	2384	267050	95375	96.9	2450	53000	136.7	4834	148375	233.6
D800-14/2607	800	14	772	2800	6676	2384	267050	95375	96.9	2600	57200	146.2	4984	152575	243.1
D800-14/2807	800	14	772	2800	6676	2384	267050	95375	96.9	2765	60830	156.7	5149	156205	253.6
D800-14/3607	800	14	772	2800	6676	2384	267050	95375	96.9	3595	89875	167.7	5979	185250	264.6
D800-14/3807	800	14	772	2800	6676	2384	267050	95375	96.9	3800	95000	179.8	6184	190375	276.7
D800-14/4007	800	14	772	2800	6676	2384	267050	95375	96.9	3970	99250	190.0	6354	194625	286.9
D800-16/2007	800	16	768	2800	7573	2705	302907	108181	110.5	1945	40845	119.4	4650	149026	229.9
D800-16/2407	800	16	768	2800	7573	2705	302907	108181	110.5	2450	53000	136.7	5155	161181	247.2
D800-16/2607	800	16	768	2800	7573	2705	302907	108181	110.5	2600	57200	146.2	5305	165381	256.7
D800-16/2807	800	16	768	2800	7573	2705	302907	108181	110.5	2765	60830	156.7	5470	169011	267.2
D800-16/3607	800	16	768	2800	7573	2705	302907	108181	110.5	3595	89875	167.7	6300	198056	278.2
D800-16/3807	800	16	768	2800	7573	2705	302907	108181	110.5	3800	95000	179.8	6505	203181	290.3
D800-16/4007	800	16	768	2800	7573	2705	302907	108181	110.5	3970	99250	190.0	6675	207431	300.5
D1000-12/2007	1000	12	976	2800	9091	3247	454544	162337	104.4	1945	40845	119.4	5192	203182	223.8
D1000-12/2407	1000	12	976	2800	9091	3247	454544	162337	104.4	2450	53000	136.7	5697	215337	241.1
D1000-12/2607	1000	12	976	2800	9091	3247	454544	162337	104.4	2600	57200	146.2	5847	219537	250.6
D1000-12/2807	1000	12	976	2800	9091	3247	454544	162337	104.4	2765	60830	156.7	6012	223167	261.1
D1000-12/3607	1000	12	976	2800	9091	3247	454544	162337	104.4	3595	89875	167.7	6842	252212	272.1
D1000-12/3807	1000	12	976	2800	9091	3247	454544	162337	104.4	3800	95000	179.8	7047	257337	284.2
D1000-12/4007	1000	12	976	2800	9091	3247	454544	162337	104.4	3970	99250	190.0	7217	261587	294.4
D1000-14/2007	1000	14	972	2800	10542	3765	527116	188256	121.6	1945	40845	119.4	5710	229101	241.0
D1000-14/2407	1000	14	972	2800	10542	3765	527116	188256	121.6	2450	53000	136.7	6215	241256	258.3
D1000-14/2607	1000	14	972	2800	10542	3765	527116	188256	121.6	2600	57200	146.2	6365	245456	267.8
D1000-14/2807	1000	14	972	2800	10542	3765	527116	188256	121.6	2765	60830	156.7	6530	249086	278.3
D1000-14/3607	1000	14	972	2800	10542	3765	527116	188256	121.6	3595	89875	167.7	7360	278131	289.3
D1000-14/3807	1000	14	972	2800	10542	3765	527116	188256	121.6	3800	95000	179.8	7565	283256	301.4
D1000-14/4007	1000	14	972	2800	10542	3765	527116	188256	121.6	3970	99250	190.0	7735	287506	311.6
D1000-16/2007	1000	16	968	2800	11976	4277	598797	213856	138.7	1945	40845	119.4	6222	254701	258.1
D1000-16/2407	1000	16	968	2800	11976	4277	598797	213856	138.7	2450	53000	136.7	6727	266856	275.4
D1000-16/2607	1000	16	968	2800	11976	4277	598797	213856	138.7	2600	57200	146.2	6877	271056	284.9
D1000-16/2807	1000	16	968	2800	11976	4277	598797	213856	138.7	2765	60830	156.7	7042	274686	295.4
D1000-16/3607	1000	16	968	2800	11976	4277	598797	213856	138.7	3595	89875	167.7	7872	303731	306.4
D1000-16/3807	1000	16	968	2800	11976	4277	598797	213856	138.7	3800	95000	179.8	8077	308856	318.5
D1000-16/4007	1000	16	968	2800	11976	4277	598797	213856	138.7	3970	99250	190.0	8247	313106	328.7
D1000-18/2007	1000	18	964	2800	13392	4783	669596	239141	155.7	1945	40845	119.4	6728	279986	275.1
D1000-18/2407	1000	18	964	2800	13392	4783	669596	239141	155.7	2450	53000	136.7	7233	292141	292.4
D1000-18/2607	1000	18	964	2800	13392	4783	669596	239141	155.7	2600	57200	146.2	7383	296341	301.9
D1000-18/2807	1000	18	964	2800	13392	4783	669596	239141	155.7	2765	60830	156.7	7548	299971	312.4
D1000-18/3607	1000	18	964	2800	13392	4783	669596	239141	155.7	3595	89875	167.7	8378	329016	323.4
D1000-18/3807	1000	18	964	2800	13392	4783	669596	239141	155.7	3800	95000	179.8	8583	334141	335.5
D1000-18/4007	1000	18	964	2800	13392	4783	669596	239141	155.7	3970	99250	190.0	8753	338391	345.7
D1000-20/2007	1000	20	960	2800	14790	5282	739518	264114	172.6	1945	40845	119.4	7227	304959	292.0
D1000-20/2407	1000	20	960	2800	14790	5282	739518	264114	172.6	2450	53000	136.7	7732	317114	309.3
D1000-20/2607	1000	20	960	2800	14790	5282	739518	264114	172.6	2600	57200	146.2	7882	321314	318.8
D1000-20/2807	1000	20	960	2800	14790	5282	739518	264114	172.6	2765	60830	156.7	8047	324944	329.3
D1000-20/3607	1000	20	960	2800	14790	5282	739518	264114	172.6	3595	89875	167.7	8877	353989	340.3
D1000-20/3807	1000	20	960	2800	14790	5282	739518	264114	172.6	3800	95000	179.8	9082	359114	352.4
D1000-20/4007	1000	20	960	2800	14790	5282	739518	264114	172.6	3970	99250	190.0	9252	363364	362.6
D1000-22/2007	1000	22	956	2800	16171	5776	808572	288776	189.5	1945	40845	119.4	7721	329621	308.9
D1000-22/2407	1000	22	956	2800	16171	5776	808572	288776	189.5	2450	53000	136.7	8226	341776	326.2
D1000-22/2607	1000	22	956	2800	16171	5776	808572	288776	189.5	2600	57200	146.2	8376	345976	335.7
D1000-22/2807	1000	22	956	2800	16171	5776	808572	288776	189.5	2765	60830	156.7	8541	349606	346.2
D1000-22/3607	1000	22	956	2800	16171	5776	808572	288776	189.5	3595	89875	167.7	9371	378651	357.2
D1000-22/3807	1000	22	956	2800	16171	5776	808572	288776	189.5	3800	95000	179.8	9576	383776	369.3
D1000-22/4007	1000	22	956	2800	16171	5776	808572	288776	189.5	3970	99250	190.0	9746	388026	379.5

Type of Wall	Steel Tubular Piles									Z Sheet Piles			Tube/Z Wall 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 m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)
D1200-14/2007	1200	14	1172	2800	15288	5460	917281	327600	146.2	1945	40845	119.4	7405	368445	265.6
D1200-14/2407	1200	14	1172	2800	15288	5460	917281	327600	146.2	2450	53000	136.7	7910	380600	282.9
D1200-14/2607	1200	14	1172	2800	15288	5460	917281	327600	146.2	2600	57200	146.2	8060	384800	292.4
D1200-14/2807	1200	14	1172	2800	15288	5460	917281	327600	146.2	2765	60830	156.7	8225	388430	302.9
D1200-14/3607	1200	14	1172	2800	15288	5460	917281	327600	146.2	3595	89875	167.7	9055	417475	313.9
D1200-14/3807	1200	14	1172	2800	15288	5460	917281	327600	146.2	3800	95000	179.8	9260	422600	326.0
D1200-14/4007	1200	14	1172	2800	15288	5460	917281	327600	146.2	3970	99250	190.0	9430	426850	336.2
D1200-16/2007	1200	16	1168	2800	17385	6209	1043072	372526	166.9	1945	40845	119.4	8154	413371	286.3
D1200-16/2407	1200	16	1168	2800	17385	6209	1043072	372526	166.9	2450	53000	136.7	8659	425526	303.6
D1200-16/2607	1200	16	1168	2800	17385	6209	1043072	372526	166.9	2600	57200	146.2	8809	429726	313.1
D1200-16/2807	1200	16	1168	2800	17385	6209	1043072	372526	166.9	2765	60830	156.7	8974	433356	323.6
D1200-16/3607	1200	16	1168	2800	17385	6209	1043072	372526	166.9	3595	89875	167.7	9804	462401	334.6
D1200-16/3807	1200	16	1168	2800	17385	6209	1043072	372526	166.9	3800	95000	179.8	10009	467526	346.7
D1200-16/4007	1200	16	1168	2800	17385	6209	1043072	372526	166.9	3970	99250	190.0	10179	471776	356.9
D1200-18/2007	1200	18	1164	2800	19460	6950	1167577	416992	187.4	1945	40845	119.4	8895	457837	306.8
D1200-18/2407	1200	18	1164	2800	19460	6950	1167577	416992	187.4	2450	53000	136.7	9400	469992	324.1
D1200-18/2607	1200	18	1164	2800	19460	6950	1167577	416992	187.4	2600	57200	146.2	9550	474192	333.6
D1200-18/2807	1200	18	1164	2800	19460	6950	1167577	416992	187.4	2765	60830	156.7	9715	477822	344.1
D1200-18/3607	1200	18	1164	2800	19460	6950	1167577	416992	187.4	3595	89875	167.7	10545	506867	355.1
D1200-18/3807	1200	18	1164	2800	19460	6950	1167577	416992	187.4	3800	95000	179.8	10750	511992	367.2
D1200-18/4007	1200	18	1164	2800	19460	6950	1167577	416992	187.4	3970	99250	190.0	10920	516242	377.4
D1200-20/2007	1200	20	1160	2800	21513	7683	1290805	461002	207.9	1945	40845	119.4	9628	501847	327.3
D1200-20/2407	1200	20	1160	2800	21513	7683	1290805	461002	207.9	2450	53000	136.7	10133	514002	344.6
D1200-20/2607	1200	20	1160	2800	21513	7683	1290805	461002	207.9	2600	57200	146.2	10283	518202	354.1
D1200-20/2807	1200	20	1160	2800	21513	7683	1290805	461002	207.9	2765	60830	156.7	10448	521832	364.6
D1200-20/3607	1200	20	1160	2800	21513	7683	1290805	461002	207.9	3595	89875	167.7	11278	550877	375.6
D1200-20/3807	1200	20	1160	2800	21513	7683	1290805	461002	207.9	3800	95000	179.8	11483	556002	387.7
D1200-20/4007	1200	20	1160	2800	21513	7683	1290805	461002	207.9	3970	99250	190.0	11653	560252	397.9
D1200-22/2007	1200	22	1156	2800	23546	8409	1412765	504559	228.3	1945	40845	119.4	10354	545404	347.7
D1200-22/2407	1200	22	1156	2800	23546	8409	1412765	504559	228.3	2450	53000	136.7	10859	557559	365.0
D1200-22/2607	1200	22	1156	2800	23546	8409	1412765	504559	228.3	2600	57200	146.2	11009	561759	374.5
D1200-22/2807	1200	22	1156	2800	23546	8409	1412765	504559	228.3	2765	60830	156.7	11174	565389	385.0
D1200-22/3607	1200	22	1156	2800	23546	8409	1412765	504559	228.3	3595	89875	167.7	12004	594434	396.0
D1200-22/3807	1200	22	1156	2800	23546	8409	1412765	504559	228.3	3800	95000	179.8	12209	599559	408.1
D1200-22/4007	1200	22	1156	2800	23546	8409	1412765	504559	228.3	3970	99250	190.0	12379	603809	418.3
D1200-25/2007	1200	25	1150	2800	26556	9484	1593346	569052	258.7	1945	40845	119.4	11429	609897	378.1
D1200-25/2407	1200	25	1150	2800	26556	9484	1593346	569052	258.7	2450	53000	136.7	11934	622052	395.4
D1200-25/2607	1200	25	1150	2800	26556	9484	1593346	569052	258.7	2600	57200	146.2	12084	626252	404.9
D1200-25/2807	1200	25	1150	2800	26556	9484	1593346	569052	258.7	2765	60830	156.7	12249	629882	415.4
D1200-25/3607	1200	25	1150	2800	26556	9484	1593346	569052	258.7	3595	89875	167.7	13079	658927	426.4
D1200-25/3807	1200	25	1150	2800	26556	9484	1593346	569052	258.7	3800	95000	179.8	13284	664052	438.5
D1200-25/4007	1200	25	1150	2800	26556	9484	1593346	569052	258.7	3970	99250	190.0	13454	668302	448.7

Table2. Tube /Z Wall (Hoesch Profile) Properties

3-4-3 Tube/Z Wall (PZC Profile)

Type of Wall	Steel Tubular Piles									Z Sheet Piles			Tube/Z Wall 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 m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)
D800-10/PZC18	800	10	780	2832	4841	1709	193647	68378	68.8	1800	34890	118.2	3509	103268	187.0
D800-10/PZC25	800	10	780	2832	4841	1709	193647	68378	68.8	2455	55190	145.9	4164	123568	214.7
D800-10/PZC26	800	10	780	2832	4841	1709	193647	68378	68.8	2600	58460	155.4	4309	126838	224.2
D800-10/PZC28	800	10	780	2832	4841	1709	193647	68378	68.8	2755	62150	166.1	4464	130528	234.9
D800-10/PZC37	800	10	780	2832	4841	1709	193647	68378	68.8	3680	98270	181.2	5389	166648	250.0
D800-10/PZC39	800	10	780	2832	4841	1709	193647	68378	68.8	3890	104100	192.8	5599	172478	261.6
D800-10/PZC41	800	10	780	2832	4841	1709	193647	68378	68.8	4090	109700	204.1	5799	178078	272.9
D800-12/PZC18	800	12	776	2832	5766	2036	230632	81438	82.3	1800	34890	118.2	3836	116328	200.5
D800-12/PZC25	800	12	776	2832	5766	2036	230632	81438	82.3	2455	55190	145.9	4491	136628	228.2
D800-12/PZC26	800	12	776	2832	5766	2036	230632	81438	82.3	2600	58460	155.4	4636	139898	237.7
D800-12/PZC28	800	12	776	2832	5766	2036	230632	81438	82.3	2755	62150	166.1	4791	143588	248.4
D800-12/PZC37	800	12	776	2832	5766	2036	230632	81438	82.3	3680	98270	181.2	5716	179708	263.5
D800-12/PZC39	800	12	776	2832	5766	2036	230632	81438	82.3	3890	104100	192.8	5926	185538	275.1
D800-12/PZC41	800	12	776	2832	5766	2036	230632	81438	82.3	4090	109700	204.1	6126	191138	286.4
D800-14/PZC18	800	14	772	2832	6676	2357	267050	94297	95.8	1800	34890	118.2	4157	129187	214.0
D800-14/PZC25	800	14	772	2832	6676	2357	267050	94297	95.8	2455	55190	145.9	4812	149487	241.7
D800-14/PZC26	800	14	772	2832	6676	2357	267050	94297	95.8	2600	58460	155.4	4957	152757	251.2
D800-14/PZC28	800	14	772	2832	6676	2357	267050	94297	95.8	2755	62150	166.1	5112	156447	261.9
D800-14/PZC37	800	14	772	2832	6676	2357	267050	94297	95.8	3680	98270	181.2	6037	192567	277.0
D800-14/PZC39	800	14	772	2832	6676	2357	267050	94297	95.8	3890	104100	192.8	6247	198397	288.6
D800-14/PZC41	800	14	772	2832	6676	2357	267050	94297	95.8	4090	109700	204.1	6447	203997	299.9
D800-16/PZC18	800	16	768	2832	7573	2674	302907	106959	109.2	1800	34890	118.2	4474	141849	227.4
D800-16/PZC25	800	16	768	2832	7573	2674	302907	106959	109.2	2455	55190	145.9	5129	162149	255.1
D800-16/PZC26	800	16	768	2832	7573	2674	302907	106959	109.2	2600	58460	155.4	5274	165419	264.6
D800-16/PZC28	800	16	768	2832	7573	2674	302907	106959	109.2	2755	62150	166.1	5429	169109	275.3
D800-16/PZC37	800	16	768	2832	7573	2674	302907	106959	109.2	3680	98270	181.2	6354	205229	290.4
D800-16/PZC39	800	16	768	2832	7573	2674	302907	106959	109.2	3890	104100	192.8	6564	211059	302.0
D800-16/PZC41	800	16	768	2832	7573	2674	302907	106959	109.2	4090	109700	204.1	6764	216659	313.3
D1000-12/PZC18	1000	12	976	2832	9091	3210	454544	160503	103.2	1800	34890	118.2	5010	195393	221.4
D1000-12/PZC25	1000	12	976	2832	9091	3210	454544	160503	103.2	2455	55190	145.9	5665	215693	249.1
D1000-12/PZC26	1000	12	976	2832	9091	3210	454544	160503	103.2	2600	58460	155.4	5810	218963	258.6
D1000-12/PZC28	1000	12	976	2832	9091	3210	454544	160503	103.2	2755	62150	166.1	5965	222653	269.3
D1000-12/PZC37	1000	12	976	2832	9091	3210	454544	160503	103.2	3680	98270	181.2	6890	258773	284.4
D1000-12/PZC39	1000	12	976	2832	9091	3210	454544	160503	103.2	3890	104100	192.8	7100	264603	296.0
D1000-12/PZC41	1000	12	976	2832	9091	3210	454544	160503	103.2	4090	109700	204.1	7300	270203	307.3
D1000-14/PZC18	1000	14	972	2832	10542	3723	527116	186129	120.2	1800	34890	118.2	5523	221019	238.4
D1000-14/PZC25	1000	14	972	2832	10542	3723	527116	186129	120.2	2455	55190	145.9	6178	241319	266.1
D1000-14/PZC26	1000	14	972	2832	10542	3723	527116	186129	120.2	2600	58460	155.4	6323	244589	275.6
D1000-14/PZC28	1000	14	972	2832	10542	3723	527116	186129	120.2	2755	62150	166.1	6478	248279	286.3
D1000-14/PZC37	1000	14	972	2832	10542	3723	527116	186129	120.2	3680	98270	181.2	7403	284399	301.4
D1000-14/PZC39	1000	14	972	2832	10542	3723	527116	186129	120.2	3890	104100	192.8	7613	290229	313.0
D1000-14/PZC41	1000	14	972	2832	10542	3723	527116	186129	120.2	4090	109700	204.1	7813	295829	324.3
D1000-16/PZC18	1000	16	968	2832	11976	4229	598797	211440	137.1	1800	34890	118.2	6029	246330	255.3
D1000-16/PZC25	1000	16	968	2832	11976	4229	598797	211440	137.1	2455	55190	145.9	6684	266630	283.0
D1000-16/PZC26	1000	16	968	2832	11976	4229	598797	211440	137.1	2600	58460	155.4	6829	269900	292.5
D1000-16/PZC28	1000	16	968	2832	11976	4229	598797	211440	137.1	2755	62150	166.1	6984	273590	303.2
D1000-16/PZC37	1000	16	968	2832	11976	4229	598797	211440	137.1	3680	98270	181.2	7909	309710	318.3
D1000-16/PZC39	1000	16	968	2832	11976	4229	598797	211440	137.1	3890	104100	192.8	8119	315540	329.9
D1000-16/PZC41	1000	16	968	2832	11976	4229	598797	211440	137.1	4090	109700	204.1	8319	321140	341.2
D1000-18/PZC18	1000	18	964	2832	13392	4729	669596	236439	153.9	1800	34890	118.2	6529	271329	272.1
D1000-18/PZC25	1000	18	964	2832	13392	4729	669596	236439	153.9	2455	55190	145.9	7184	291629	299.8
D1000-18/PZC26	1000	18	964	2832	13392	4729	669596	236439	153.9	2600	58460	155.4	7329	294899	309.3
D1000-18/PZC28	1000	18	964	2832	13392	4729	669596	236439	153.9	2755	62150	166.1	7484	298589	320.0
D1000-18/PZC37	1000	18	964	2832	13392	4729	669596	236439	153.9	3680	98270	181.2	8409	334709	335.1
D1000-18/PZC39	1000	18	964	2832	13392	4729	669596	236439	153.9	3890	104100	192.8	8619	340539	346.7
D1000-18/PZC41	1000	18	964	2832	13392	4729	669596	236439	153.9	4090	109700	204.1	8819	346139	358.0
D1000-20/PZC18	1000	20	960	2832	14790	5223	739518	261129	170.7	1800	34890	118.2	7023	296019	288.9
D1000-20/PZC25	1000	20	960	2832	14790	5223	739518	261129	170.7	2455	55190	145.9	7678	316319	316.6
D1000-20/PZC26	1000	20	960	2832	14790	5223	739518	261129	170.7	2600	58460	155.4	7823	319589	326.1
D1000-20/PZC28	1000	20	960	2832	14790	5223	739518	261129	170.7	2755	62150	166.1	7978	323279	336.8
D1000-20/PZC37	1000	20	960	2832	14790	5223	739518	261129	170.7	3680	98270	181.2	8903	359399	351.9
D1000-20/PZC39	1000	20	960	2832	14790	5223	739518	261129	170.7	3890	104100	192.8	9113	365229	363.5
D1000-20/PZC41	1000	20	960	2832	14790	5223	739518	261129	170.7	4090	109700	204.1	9313	370829	374.8
D1000-22/PZC18	1000	22	956	2832	16171	5710	808572	285513	187.4	1800	34890	118.2	7510	320403	305.6
D1000-22/PZC25	1000	22	956	2832	16171	5710	808572	285513	187.4	2455	55190	145.9	8165	340703	333.3
D1000-22/PZC26	1000	22	956	2832	16171	5710	808572	285513	187.4	2600	58460	155.4	8310	343973	342.8
D1000-22/PZC28	1000	22	956	2832	16171	5710	808572	285513	187.4	2755	62150	166.1	8465	347663	353.5
D1000-22/PZC37	1000	22	956	2832	16171	5710	808572	285513	187.4	3680	98270	181.2	9390	383783	368.6
D1000-22/PZC39	1000	22	956	2832	16171	5710	808572	285513	187.4	3890	104100	192.8	9600	389613	380.2
D1000-22/PZC41	1000	22	956	2832	16171	5710	808572	285513	187.4	4090	109700	204.1	9800	395213	391.5

Type of Wall	Steel Tubular Piles									Z Sheet Piles			Tube/Z Wall 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 m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)	Section Modulus Z (cm^3/m)	Moment of Inertia I (cm^4/m)	Mass per m^2 of wall (kg/m^2)
D1200-14/PZC18	1200	14	1172	2832	15288	5398	917281	323899	144.6	1800	34890	118.2	7198	358789	262.8
D1200-14/PZC25	1200	14	1172	2832	15288	5398	917281	323899	144.6	2455	55190	145.9	7853	379089	290.5
D1200-14/PZC26	1200	14	1172	2832	15288	5398	917281	323899	144.6	2600	58460	155.4	7998	382359	300.0
D1200-14/PZC28	1200	14	1172	2832	15288	5398	917281	323899	144.6	2755	62150	166.1	8153	386049	310.7
D1200-14/PZC37	1200	14	1172	2832	15288	5398	917281	323899	144.6	3680	98270	181.2	9078	422169	325.8
D1200-14/PZC39	1200	14	1172	2832	15288	5398	917281	323899	144.6	3890	104100	192.8	9288	427999	337.4
D1200-14/PZC41	1200	14	1172	2832	15288	5398	917281	323899	144.6	4090	109700	204.1	9488	433599	348.7
D1200-16/PZC18	1200	16	1168	2832	17385	6139	1043072	368316	165.0	1800	34890	118.2	7939	403206	283.2
D1200-16/PZC25	1200	16	1168	2832	17385	6139	1043072	368316	165.0	2455	55190	145.9	8594	423506	310.9
D1200-16/PZC26	1200	16	1168	2832	17385	6139	1043072	368316	165.0	2600	58460	155.4	8739	426776	320.4
D1200-16/PZC28	1200	16	1168	2832	17385	6139	1043072	368316	165.0	2755	62150	166.1	8894	430466	331.1
D1200-16/PZC37	1200	16	1168	2832	17385	6139	1043072	368316	165.0	3680	98270	181.2	9819	466586	346.2
D1200-16/PZC39	1200	16	1168	2832	17385	6139	1043072	368316	165.0	3890	104100	192.8	10029	472416	357.8
D1200-16/PZC41	1200	16	1168	2832	17385	6139	1043072	368316	165.0	4090	109700	204.1	10229	478016	369.1
D1200-18/PZC18	1200	18	1164	2832	19460	6871	1167577	412280	185.3	1800	34890	118.2	8671	447170	303.5
D1200-18/PZC25	1200	18	1164	2832	19460	6871	1167577	412280	185.3	2455	55190	145.9	9326	467470	331.2
D1200-18/PZC26	1200	18	1164	2832	19460	6871	1167577	412280	185.3	2600	58460	155.4	9471	470740	340.7
D1200-18/PZC28	1200	18	1164	2832	19460	6871	1167577	412280	185.3	2755	62150	166.1	9626	474430	351.4
D1200-18/PZC37	1200	18	1164	2832	19460	6871	1167577	412280	185.3	3680	98270	181.2	10551	510550	366.5
D1200-18/PZC39	1200	18	1164	2832	19460	6871	1167577	412280	185.3	3890	104100	192.8	10761	516380	378.1
D1200-18/PZC41	1200	18	1164	2832	19460	6871	1167577	412280	185.3	4090	109700	204.1	10961	521980	389.4
D1200-20/PZC18	1200	20	1160	2832	21513	7597	1290805	455793	205.5	1800	34890	118.2	9397	490683	323.7
D1200-20/PZC25	1200	20	1160	2832	21513	7597	1290805	455793	205.5	2455	55190	145.9	10052	510983	351.4
D1200-20/PZC26	1200	20	1160	2832	21513	7597	1290805	455793	205.5	2600	58460	155.4	10197	514253	360.9
D1200-20/PZC28	1200	20	1160	2832	21513	7597	1290805	455793	205.5	2755	62150	166.1	10352	517943	371.6
D1200-20/PZC37	1200	20	1160	2832	21513	7597	1290805	455793	205.5	3680	98270	181.2	11277	554063	386.7
D1200-20/PZC39	1200	20	1160	2832	21513	7597	1290805	455793	205.5	3890	104100	192.8	11487	559893	398.3
D1200-20/PZC41	1200	20	1160	2832	21513	7597	1290805	455793	205.5	4090	109700	204.1	11687	565493	409.6
D1200-22/PZC18	1200	22	1156	2832	23546	8314	1412765	498858	225.7	1800	34890	118.2	10114	533748	343.9
D1200-22/PZC25	1200	22	1156	2832	23546	8314	1412765	498858	225.7	2455	55190	145.9	10769	554048	371.6
D1200-22/PZC26	1200	22	1156	2832	23546	8314	1412765	498858	225.7	2600	58460	155.4	10914	557318	381.1
D1200-22/PZC28	1200	22	1156	2832	23546	8314	1412765	498858	225.7	2755	62150	166.1	11069	561008	391.8
D1200-22/PZC37	1200	22	1156	2832	23546	8314	1412765	498858	225.7	3680	98270	181.2	11994	597128	406.9
D1200-22/PZC39	1200	22	1156	2832	23546	8314	1412765	498858	225.7	3890	104100	192.8	12204	602958	418.5
D1200-22/PZC41	1200	22	1156	2832	23546	8314	1412765	498858	225.7	4090	109700	204.1	12404	608558	429.8
D1200-25/PZC18	1200	25	1150	2832	26556	9377	1593346	562622	255.8	1800	34890	118.2	11177	597512	374.0
D1200-25/PZC25	1200	25	1150	2832	26556	9377	1593346	562622	255.8	2455	55190	145.9	11832	617812	401.7
D1200-25/PZC26	1200	25	1150	2832	26556	9377	1593346	562622	255.8	2600	58460	155.4	11977	621082	411.2
D1200-25/PZC28	1200	25	1150	2832	26556	9377	1593346	562622	255.8	2755	62150	166.1	12132	624772	421.9
D1200-25/PZC37	1200	25	1150	2832	26556	9377	1593346	562622	255.8	3680	98270	181.2	13057	660892	437.0
D1200-25/PZC39	1200	25	1150	2832	26556	9377	1593346	562622	255.8	3890	104100	192.8	13267	666722	448.6
D1200-25/PZC41	1200	25	1150	2832	26556	9377	1593346	562622	255.8	4090	109700	204.1	13467	672322	459.9

Table3. Tube /Z Wall (PZC Profile) 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

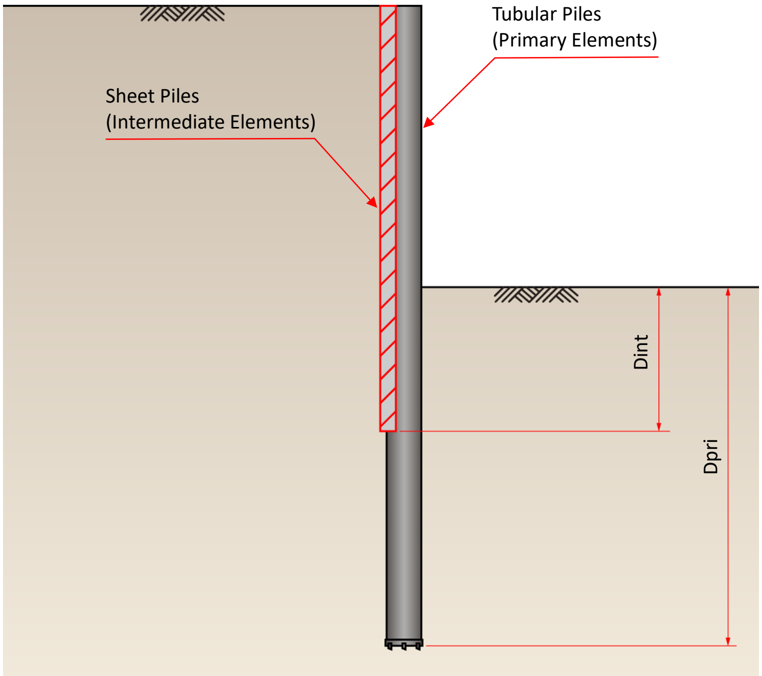


Figure 4. Orientation Pattern A

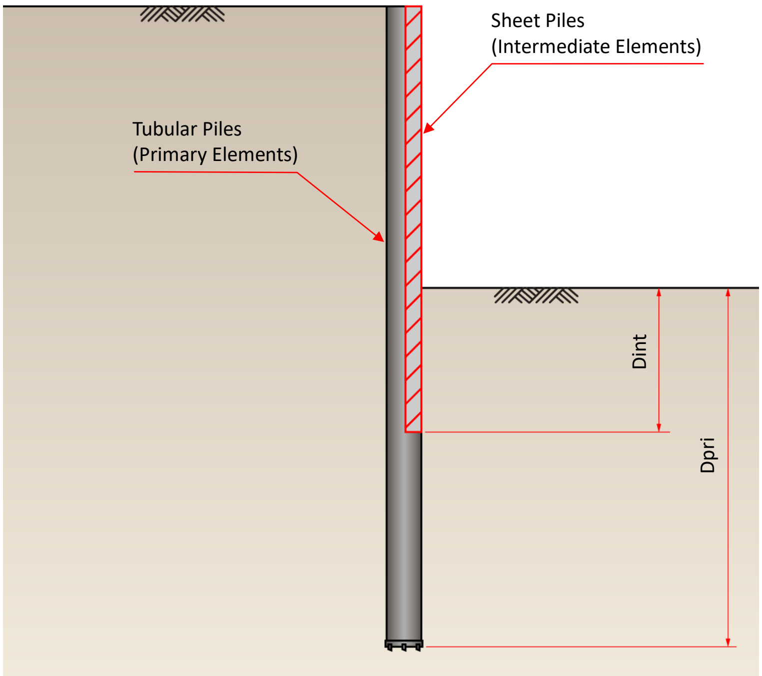


Figure 5. Orientation Pattern B

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.

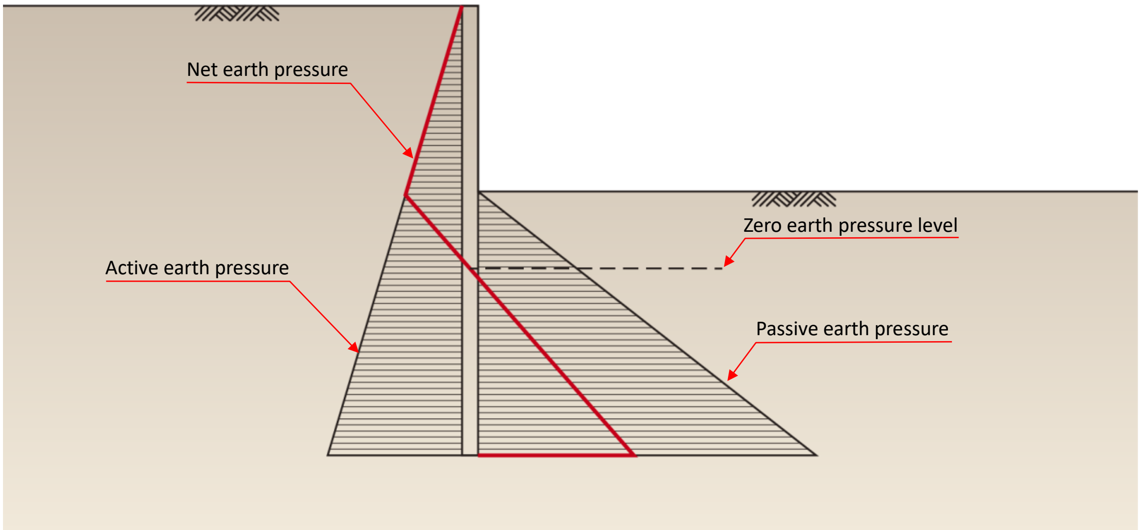


Figure6. Schematic earth pressure diagram

4-3 Passive Mobilisation Mechanism

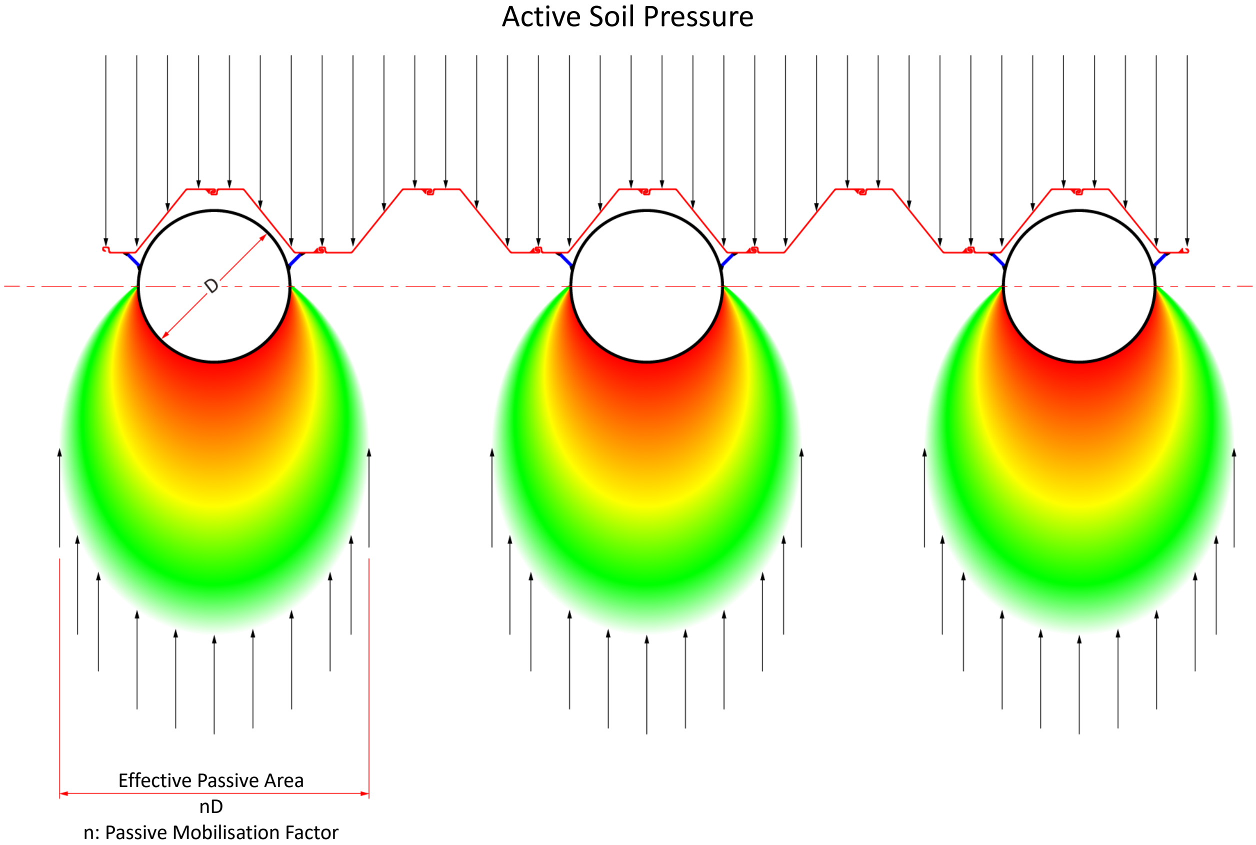


Figure 7. Schematic effective area for passive soil pressure

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.

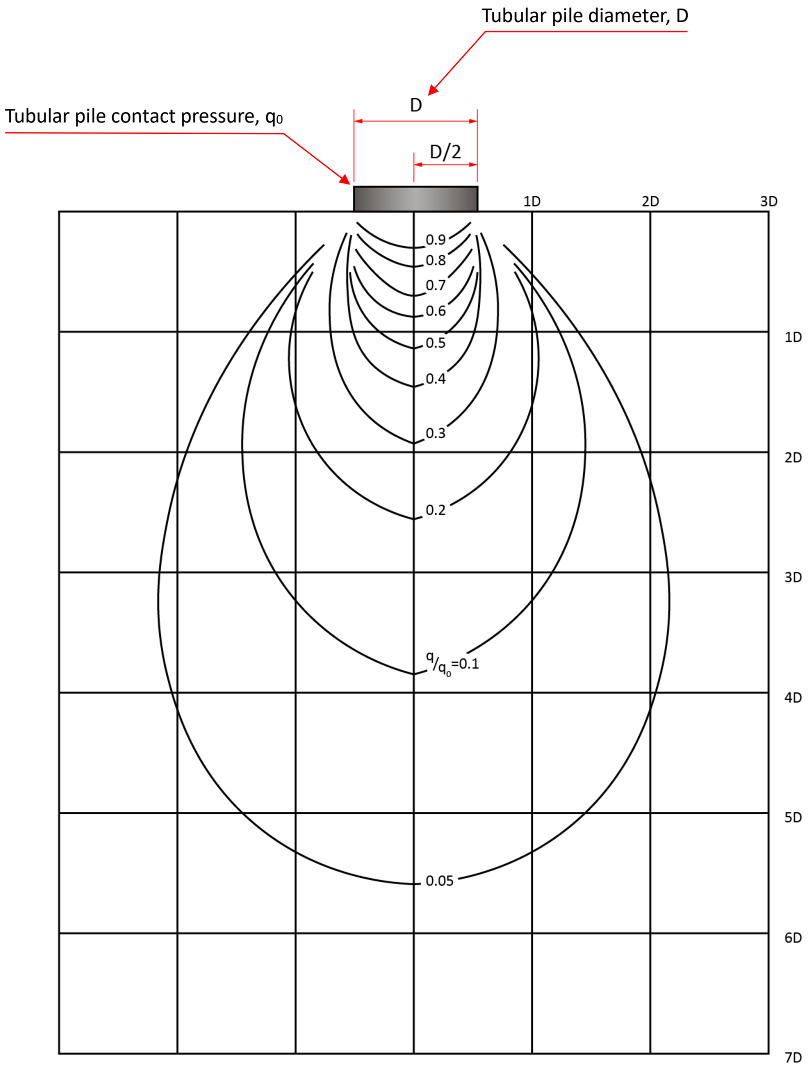


Figure 8. Pressure bulbs formed on the passive side of a tubular pile, showing the intensity of pressure q/q0,based on the Boussinesq equation (after Bowles [1996])

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

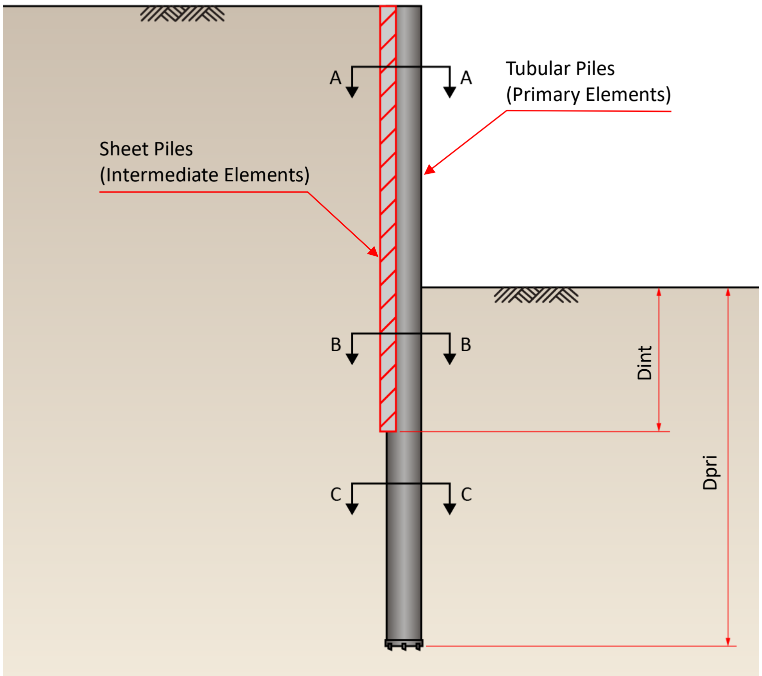


Figure 9(a). Combi-Gyro Wall - Section (Pattern A)

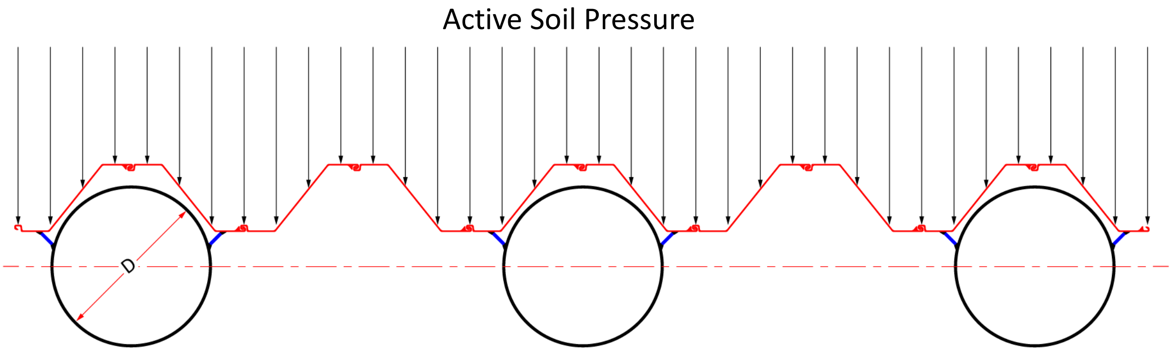


Figure 9(b). Earth pressure diagram - Plan in section A-A (Pattern A, above formation level)

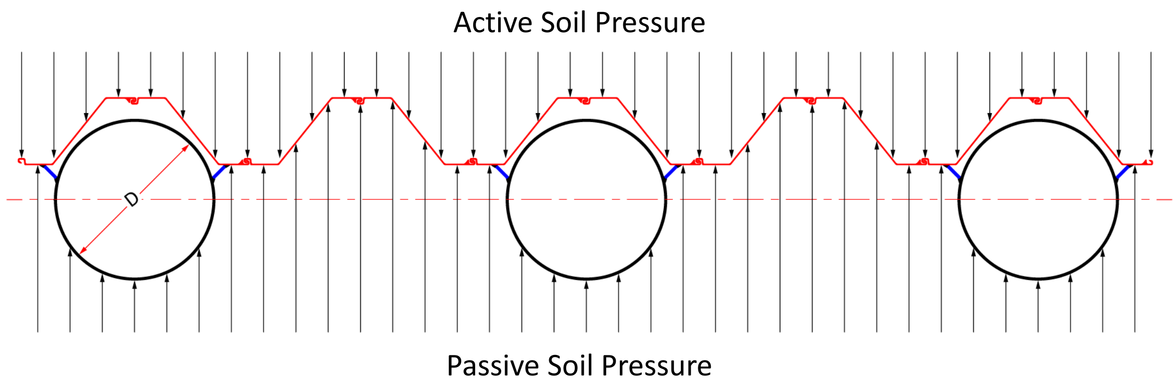


Figure 9(c). Earth pressure diagram - Plan in section B-B (Pattern A, above SSP toe level)

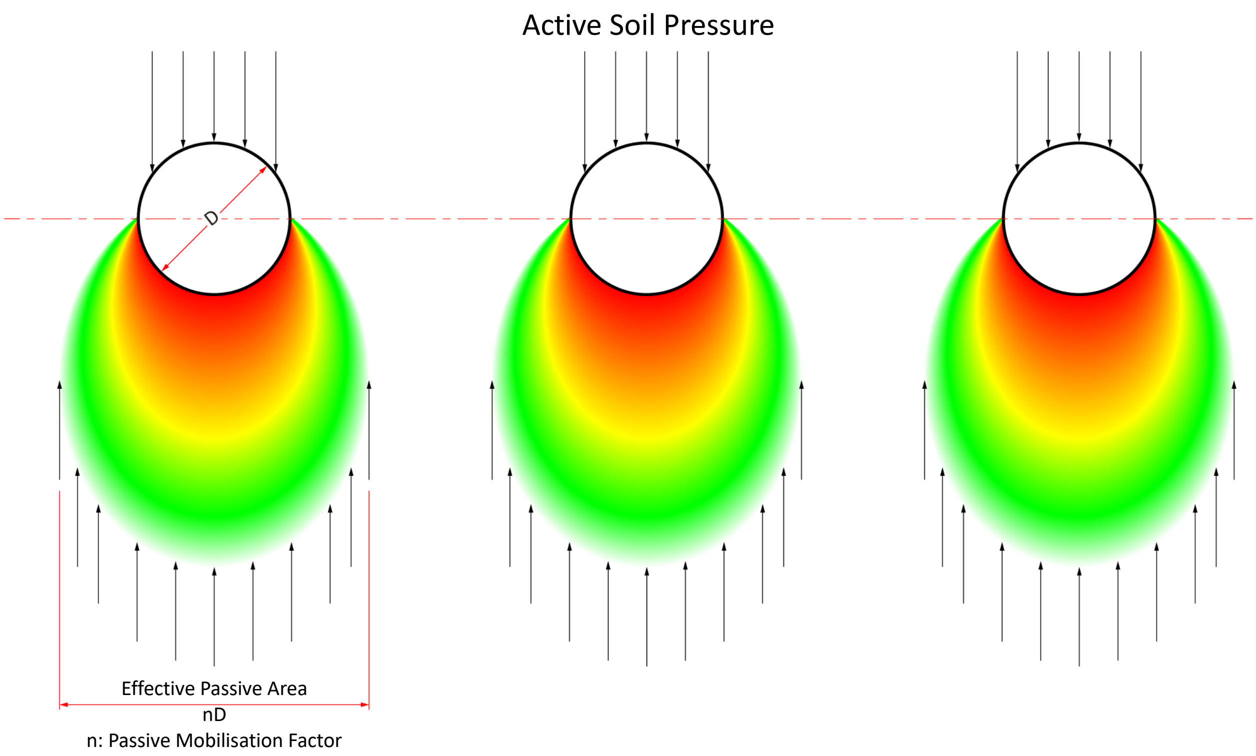


Figure 9(d). Earth pressure diagram - Plan in section C-C (Pattern A, below SSP toe level)

4-3-2 Orientation Pattern B

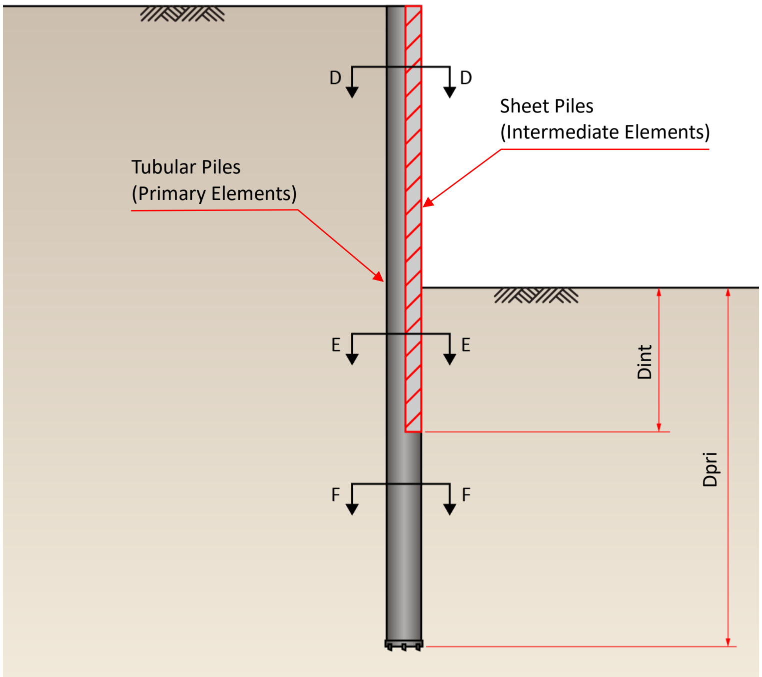


Figure 10(a). Combi-Gyro Wall - Section (Pattern B)

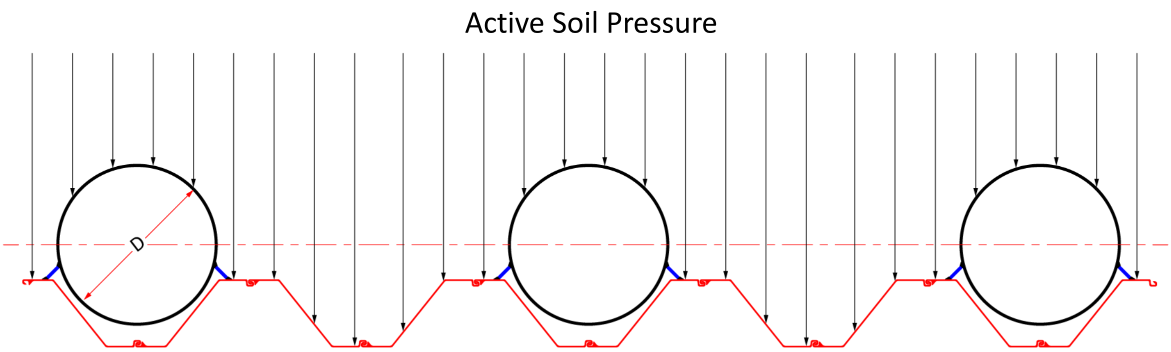


Figure 10(b). Earth pressure diagram - Plan in section D-D (Pattern B, above formation level)

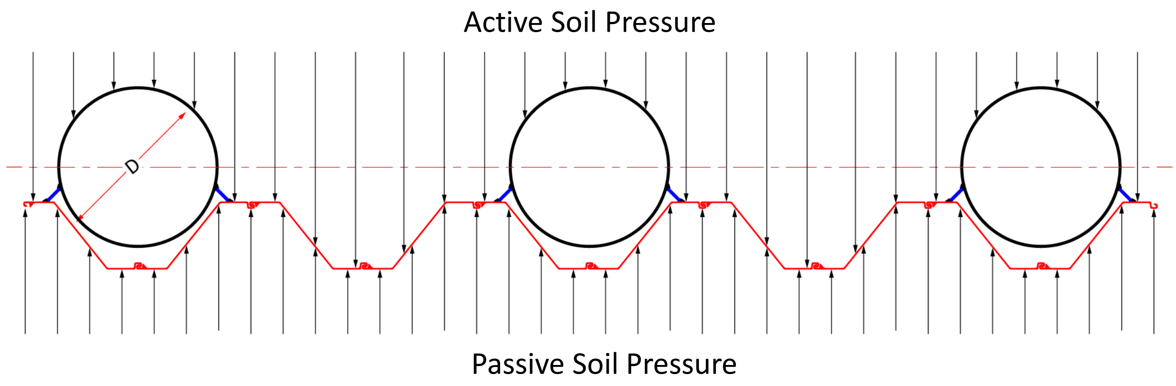


Figure 10(c). Earth pressure diagram - Plan in section E-E (Pattern B, above SSP toe level)

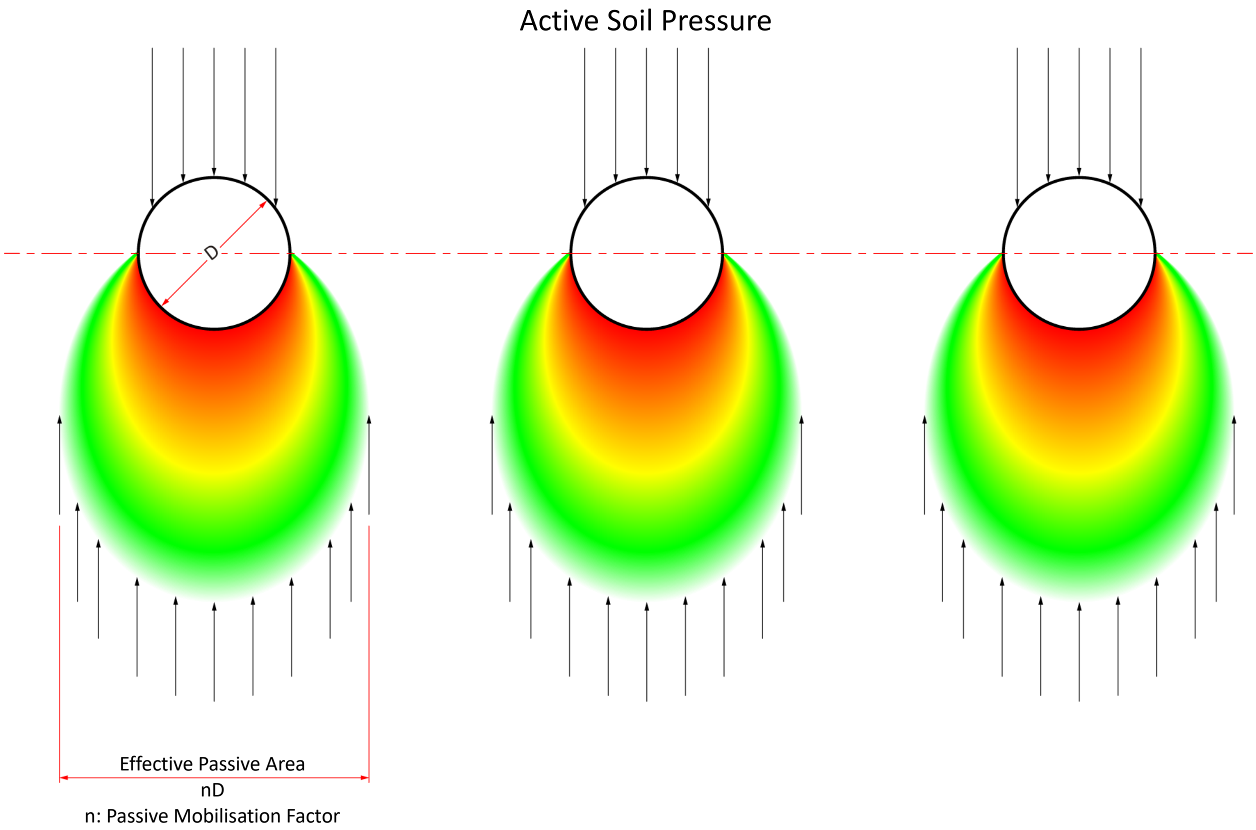


Figure 10(d). Earth pressure diagram - Plan in section F-F (Pattern B, below SSP toe level)

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 4. 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

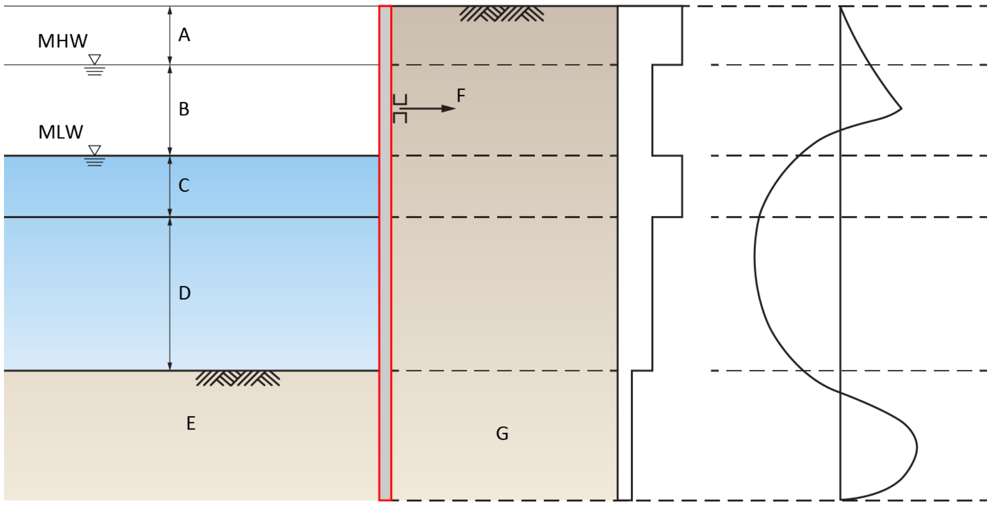
Environments	5 years	25years	50years	75years	100years	125years
Common fresh water (river, ship canal…) in the zone of high attack(water line)	0.15	0.55	0.90	1.15	1.40	1.65
Very polluted fresh water (sewage, industrial effluent…) in the zone of high attack (water line)	0.30	1.30	2.30	3.30	4.30	5.30
Sea 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 5. 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.



a) Vertical zoning of sea water aggressivity

b) Corrosion rate distribution at side exposed to sea water

c) Typical bending moment distribution

A	Zone of high attack (splash zone);	B	Intertidal zone;
C	Zone of high attack (Low water zone);	D	Permanent immersion zone;
E	Buried zone (Water side);	F	Anchor;
G	Buried zone (Soil side)		
MHW	Mean high water;	MLW	Mean low water

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).

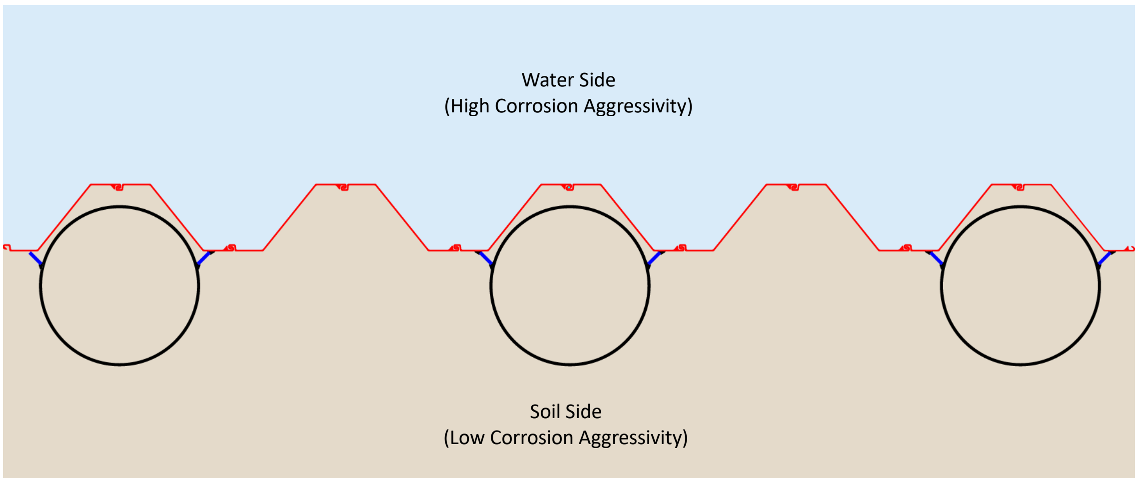


Figure 12. Wall Orientation for Waterfront Structure

Chapter 5 Design Case Study

5-1 Introduction

These calculations detail the design of a cantilevered Combi-Gyro Wall (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 1000mm external diameter (with the wall thickness of 16mm) at 2.8m centres and continuous AZ 28-700N steel sheet 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 (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 these two wall designs and a comparison of the cantilevered Combi-Gyro Wall (Pattern A) and Secant Piled Wall will be presented in this section.

5-2 List of Design Standards and References

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- Hight, D.W., McMillan, F., Powell, J.J.M., Jardine, R.J. and Allenou, C.P. [2003] Some characteristics of London Clay. Proc. Conf. Characterisation and Engineering, National University Singapore, Balkema, Vol. 2, pp. 851-907.
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- Peck, R.B., Hanson, W.E. and Thornburn, T.H. [1974] Foundation Engineering, Wiley, New York.
- Plaxis b.v. [2014] Plaxis 2D Anniversary Edition - Material Model Manual.
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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 6.

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, v'	Undrained Poisson's ratio	K_0	Coefficient of permeability. K (m/s)	Dilatancy angle for drained analysis (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 6. 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 ν_u = 0.49 assigned since ν_u = 0.50 would results in an infinite value of bulk modulus in Plaxis analysis (after Plaxis b.v. [2014]).
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 Eid et al.[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 $E' = E_u (1+v') / (1+\nu_u)$.
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 7.

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

Table 7. 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 (Version 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 two-dimensional (2D) finite element (FE) software package, Plaxis 2D (ver. AE.02). 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 8. 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 8. 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 25mm.

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 9).

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 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.

Table 9. 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 (Pattern A)

The Combi-Gyro Wall (Pattern A) analysed in this design exercise is comprised of steel tubular piles of 1000mm external diameter at 2.8m centres with the wall thickness of 16mm and steel sheet piles AZ 28-700N. From the wall properties table, provided by Giken, values of the moment of inertia for each wall member were determined as follows:

$$I_{sys} = I_{stp} + I_{ssp}$$
$$= 213{,}856 + 63{,}700 = 277{,}556 \text{ [cm}^4\text{/m]}$$

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 (D1000-16 with AZ 28-700N) in terms of the maximum wall top deflection (i.e. ≈ 25mm).

Based on the sensitivity analyses, 900mm diameter bored piles (hard/firm) with a male-to-male spacing of 1200mm (300mm 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.

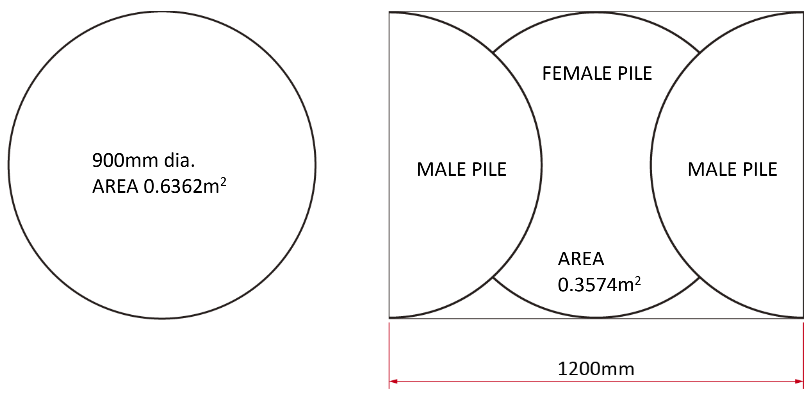

Figure 13. Arrangement of Secant Piled Wall

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:

$I_{spw} = I_{male} / d$

$= \pi r^4 / 4 / d = \pi (0.90/2)^4 / 4 / 1.2 = 2{,}683{,}853$ [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 10.

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

Table 10. 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 (Pattern A)

1) Summary of Results

Results of WALLAP runs and design summary of retaining wall calculations for the Combi-Gyro Wall (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 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	1.64	261	2.30	82	4.50	1.35	352	111	**26**
ULS - Comb.1	-	326	1.60	94	4.00	1.35	**440**	**127**	-
ULS - Comb.2	**1.09**	563	0.80	137	3.50	1.00	563	137	-

Table 11. Summary of results from WALLAP analysis on the Combi-Gyro 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 Combi-Gyro Wall has been determined as a minimum factor of safety = 1.09 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 440 kNm/m and 127 kN/m, respectively, as presented in Table 11.
The minimum required section modulus for the wall can be calculated as follows:

$S_{req} = M_d / f_y$

$= 440 \cdot 10^3 / 390 = 1128$ [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/Z 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} = 7042 [cm³/m] (> 1128, OK)
- Section modulus of the steel tubular pile: S_{stp} = 4277 [cm³/m] (> 1128, OK)
- Section modulus of the steel sheet pile: S_{ssp} = 2765 [cm³/m] (> 1128, 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 12.

Figure ref.	Plaxis Output Plots
Figure B.1	Connectivity plot
Figure B.2	Deformed mesh $\lvert u \rvert$
Figure B.3	Total vertical displacements u_y
Figure B.4	Total horizontal displacements u_x
Figure B.5	Vector of total displacements $\lvert u \rvert$
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 D1000-16
Figure B.9	Profile of wall bending moment for CHS D1000-16
Figure B.10	Profile of wall shear force for CHS D1000-16
Figure B.11	Profile of horizontal wall displacements for AZ 28-700N
Figure B.12	Profile of wall bending moment for AZ 28-700N
Figure B.13	Profile of wall shear force for AZ 28-700N

Table 12. Summary of output plots from Plaxis 2D FE analysis for Combi-Gyro Wall 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 (-170.5 kNm/m), the steel sheet pile's contribution to resist the bending moment is relatively small (-39.28 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 (170.5 + 39.28 ≈ 210 kNm/m) can be compared to the calculated maximum bending moment based on the WALLAP SLS analysis as presented in Table 11. 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 "Combi-Gyro Wall_Toe-5mOD_Fmn+4_5mOD_LT_ULS1" provided in Appendix A, the net pressure becomes zero at an approximate elevation of 3.8m AOD at Stage No. 6. 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 3.8m 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 11. 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 can be reduced if further 2D FE analyses are carried out using stress- and strain-dependant hardening soil constitutive models with small strain stiffness.

The predicted ground settlement, based on the Plaxis output plots presented in Figures B.2 to B.5 (Appendix B), is 20mm at immediately back of 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 13.

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	246	2.30	79	4.50	1.35	332	107	**25**
ULS - Comb.1	-	309	1.60	90	4.00	1.35	**417**	**122**	-
ULS - Comb.2	**1.14**	511	0.80	131	3.50	1.00	511	131	-

Table 13. 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 13.

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 417 kNm/m and 122 kN/m, respectively, as presented in Table 13. These values are similar to the recorded 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 14.

Figure ref.	Plaxis Output Plots
Figure D.1	Connectivity plot
Figure D.2	Deformed mesh $\lvert u \rvert$
Figure D.3	Total vertical displacements u_y
Figure D.4	Total horizontal displacements u_x
Figure D.5	Vector of total displacements $\lvert u \rvert$
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 14. Summary of output plots from Plaxis 2D FE analysis for Secant Piled Wall provided in Appendix D

The bending moments calculated by the Plaxis analysis (220.5 kNm/m, shown in Figure D.9) can be compared to the calculated maximum bending moment (246 kNm/m) based on the WALLAP SLS analysis as presented in Table 13.

5) Female Piles Toe Level
According to the results from the ULS - Combination 1 analysis, as reported in "Secant Piled Wall_Toe-5mOD_Fmn+4_5mOD_LT_ULS1" 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 25mm at the long-term case as presented in Table 13. Based on the Plaxis 2D FE analysis under the same loading conditions, the wall movement was predicted to be 27mm as shown in Figure D.8 (Appendix D).

It should be noted that the magnitude of the wall displacements can be reduced if further 2D FE analyses are carried out using stress- and strain-dependant hardening soil constitutive models with small strain stiffness.

The predicted ground settlement, based on the Plaxis output plots presented in Figures D.2 to D.5 (Appendix D), is 24mm 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.

5-8 Summary

The designs of the Combi-Gyro Wall and the Secant Piled Wall are compared in Table 15.

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	D1000-16	15.0	2.8	-	1.09	440	127	26
	Steel S 390 GP	AZ 28-700N	11.0	1.4	-				
Secant Piled Wall	Concrete C 30/37	900mm dia. (male)	15.0	1.2	(8 x B25) x 15m 600mm OD B12 hoop at 300mm c/c	1.14	417	122	25
	Concrete C 8/10	900mm dia. (female)	11.0	1.2	-				

Table 15. 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 Secant Piled Wall (Rev.3)

C-2. WALLAP run ID: Secant Piled Wall Toe-5mOD Fmn+4 5mOD LT SLS (Rev.2)

C-3. WALLAP run ID: Secant Piled Wall Toe-5mOD Fmn+4 5mOD LT ULS1 (Rev.2)

C-4. WALLAP run ID: Secant Piled Wall Toe-5mOD Fmn+4 5mOD LT ULS2 (Rev.2)

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
Figure D.9	Profile of wall bending moment for secant piles
Figure D.10	Profile of wall shear force for secant piles

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