Design and Construction of a Precast Ultra-High Performance Concrete Cantilever Retaining Wall

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Abstract: The design and construction of a precast ultra-high performance concrete (UHPC) cantilever retaining wall (hereafter referred to as the UHPC wall) is reported in this study. Structural design of the UHPC wall is carried out on the basis of taking benefits from revolutionary properties of UHPC, which enable the authors to design thin concrete sections. The dimensions of the UHPC wall are determined based on the stability and bearing pressure requirements in accordance with Eurocode 7-Geotechnical Design. The UHPC wall is 2 m (6.56 ft.) long, 2 m (6.56 ft.) wide, and 2.5 m (8.2 ft.) high. It consists of two integrated thin UHPC slabs, which act as the wall base and the vertical wall stem. The 40 mm (1.57 in) thick wall base is strengthened with two 80 mm (3.15 in.) thick and 100 mm (3.94 in.) wide steel reinforced stiffeners. The 30 mm (1.18 in.) thick vertical wall stem is also strengthened with two steel reinforced stiffeners, spaced across the wall stem at a distance of 1.25 m (4.1 ft.). The UHPC wall is structurally designed based on the first principles in conjunction with the Japanese Society of Civil Engineers recommendations for design and construction of UHPC structures. The essence of analysis and design procedures are highlighted. The environmental performance evaluation verifies that the precast UHPC wall with superior performance is a promising sustainable alternative to the "conventional" precast reinforced concrete (RC) cantilever retaining walls offering 86% less material consumption, 60% less CO_2 emissions, 57% less energy consumption, and 61% less global warming potential. Advantages of the UHPC wall compared to the "conventional" RC wall are also presented.

Keywords: Precast cantilever retaining wall, Ultra-high performance concrete, CO_2 emissions, embodied energy, global warming potential, Eurocode 7, Eurocode 2, Structural performance, Environmental performance, Material sustainability.

1. Introduction

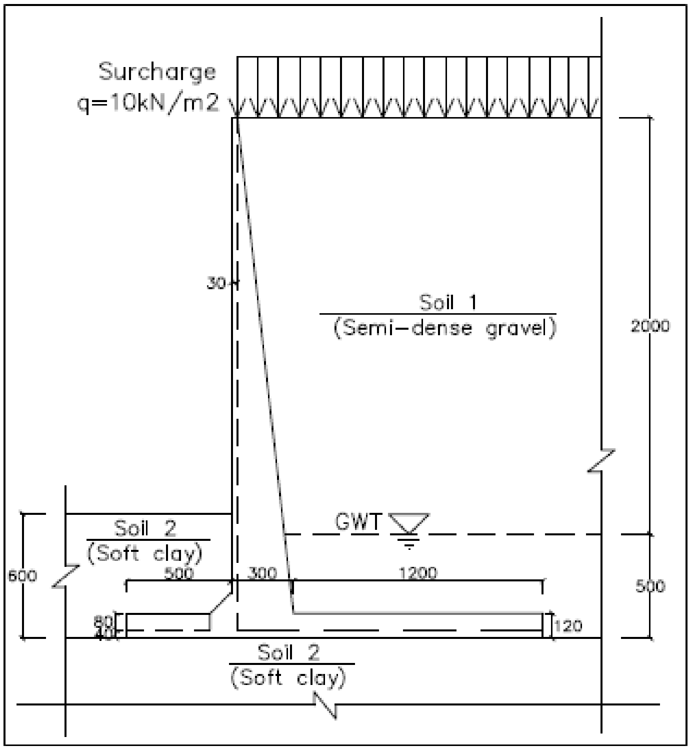
Significant advances in the field of concrete technology have been demonstrated over the past two decades. Development of ultra-high performance concrete (UHPC) was one of the main breakthroughs in the concrete technology in the 20th century. UHPC is a special class of high performance fiber reinforced cementitious composites with characteristic compressive strength, tensile strength and first cracking strength beyond 150 MPa (22 ksi), 5 MPa (0.73 ksi) and 4 MPa (0.58 ksi), respectively (JSCE No. 9, 2006). Durability of UHPC is significantly enhanced as compared to conventional and high performance concretes, thanks to its discontinuous pore structure that reduces liquid ingress (Graybeal and Tanesi, 2007). Due to detrimental effects of global warming, it is beneficial to minimize the environmental footprints of our structural designs (Nematollahi et al., 2014a). The revolutionary mechanical and durability properties of UHPC make it a promising sustainable construction material, which promotes sustainability of the infrastructures via concurrent improvements of material greenness and infrastructure durability (Nematollahi et al., 2012).

Most of the available studies on the structural application of UHPC have been focused on the experimental tests of the UHPC beams (especially prestressed beams) designed to fail in bending and/or shear (Voo et al., 2010; Voo and Foster, 2009; Voo et al., 2006). Application of UHPC in other structural members such as geotechnical-related members has received less attention. Recently, UHPCs pile for deep foundations have been designed and their performance have been verified (Voort et al., 2008). Thanks to the remarkable properties of UHPC, it offers significant benefits when it is used in the construction of precast elements such as precast cantilever retaining walls. The objective of this study is to design and construct a precast UHPC cantilever retaining wall to be used as a sustainable alternative to the “conventional” precast reinforced concrete (RC) cantilever retaining wall. Analysis and design procedures of the proposed UHPC cantilever retaining wall are briefly reviewed in the following sections. The environmental performance of the precast UHPC cantilever retaining wall is compared against the “conventional” precast RC cantilever retaining wall. Advantages of the precast UHPC cantilever retaining wall compared to the “conventional” precast RC cantilever retaining wall are also highlighted.

2. Analysis and Design of Precast UHPC Cantilever Retaining Wall

The dimensions of the precast UHPC cantilever retaining wall (hereafter referred to as the UHPC wall) are determined to satisfy the stability and bearing pressure requirements in accordance with Eurocode 7-Geotechnical Design (BS EN 1997-1, 2004). The soil properties, ground water table (GWT) and loading conditions adopted for analysis of the UHPC wall are illustrated in Figure 1.The proposed UHPC wall has the dimensions of 2 m (6.56 ft.) in length, 2 m (6.56 ft.) in width, and 2.5 m (8.2 ft.) in height. The objective of the stability analysis is to ensure that the UHPC wall with the given dimensions is stable in terms of overturning and sliding under the action of the loads corresponding to the ULS (EQU) and the ULS (GEO), respectively. The UHPC wall is also checked against bearing resistance failure of the foundation under the action of the loads corresponding to the ULS (GEO). The assumptions made in the geotechnical analysis and calculation procedures for the stability and bearing pressure analyses can be found in Nematollahi et al. (2014b).

Figures 2 and 3 present the drawings of the precast UHPC wall. As can be seen, it consists of two integrated thin UHPC slabs which act as the wall base and the vertical wall stem. The 40 mm (1.57 in.) thick wall base is strengthened with two 80 mm (3.15 in.) thick and 100 mm (3.94 in.) wide steel reinforced stiffeners, as shown in Figure 2. The 30 mm (1.18 in.) thick vertical wall stem is also strengthened with two steel reinforced stiffeners, spaced across the vertical wall stem at a distance of 1.25 m (4.1ft.), as illustrated in Figures 2 and 3. The action of possible hydrostatic pressure due to the percolating water during rain at the back face of the UHPC wall is reduced by arrangement of six weep holes with the diameter of 75 mm (2.95 in.) in the vertical wall stem, as shown in Figure 2. Once the geotechnical analyses are completed, the structural design of the UHPC wall are then carried out based on the first principles (equilibrium equations) in conjunction with the Japanese Society of Civil Engineers (JSCE) recommendations for design and construction of ultra-high strength fiber reinforced concrete structures (JSCE No.9, 2006). The objective of the structural design is to ensure $M_{Ed} \leq M_{Rd}$ in different critical cross sections of the UHPC wall, where M_{Ed} is the design moment effect and M_{Rd} is the design moment resistance under the action of the loads corresponding to the ULS (STR). The M_{Rd} of stem, heel and toe cross sections of the UHPC wall are calculated using equilibrium equations in conjunction with JSCE No.9 (2006) recommendations. The M_{Ed} of stem, heel and toe cross sections of the UHPC wall are also determined under different load combinations corresponding to the ULS (STR). The procedures for calculating the M_{Rd} and M_{Ed} of different cross sections of the UHPC wall can be found in Nematollahi et al. (2014b). As can be seen in Table 1, in all critical cross sections of the UHPC wall $M_{Ed} \leq M_{Rd}$, thus the structural design of the UHPC wall is satisfactory.



Soil properties	Soil type	
	Soil 1	Soil 2
Weight density (γ); kN/m³	17	17
Saturated weight density (γ_{sat}); kN/m³	20.5	17
Effective cohesion (c')	0	22
Characteristic angle of shearing resistance ($\varnothing'_k$)	30°	35°
Critical state angle of shearing resistance ($\varnothing'_{cv}$)	30°	35°

Figure 1. Soil properties, ground water table and loading conditions

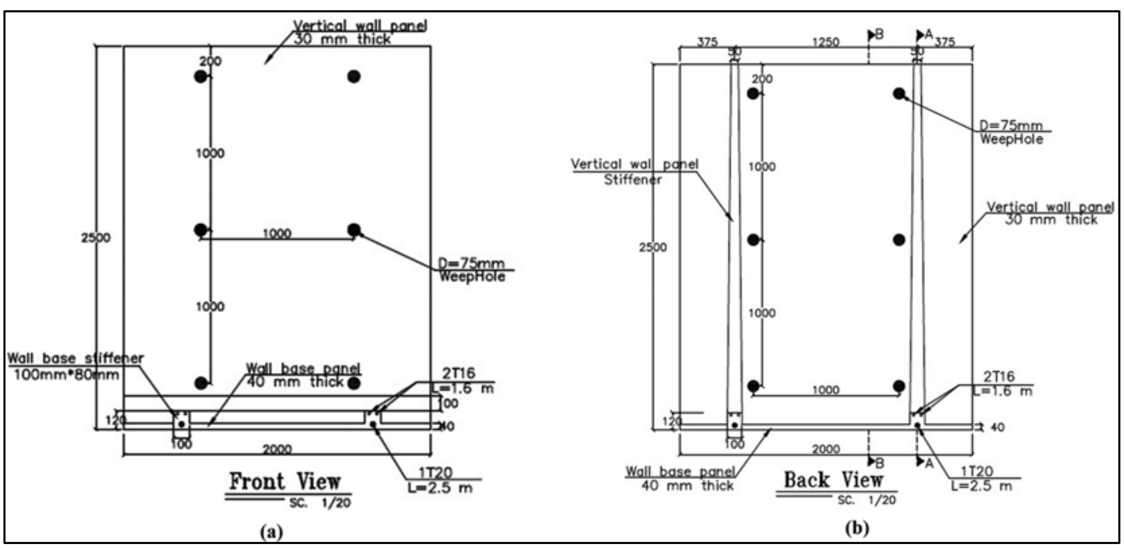


Figure 2. (a) Front view and (b) Back view of precast UHPC cantilever retaining wall

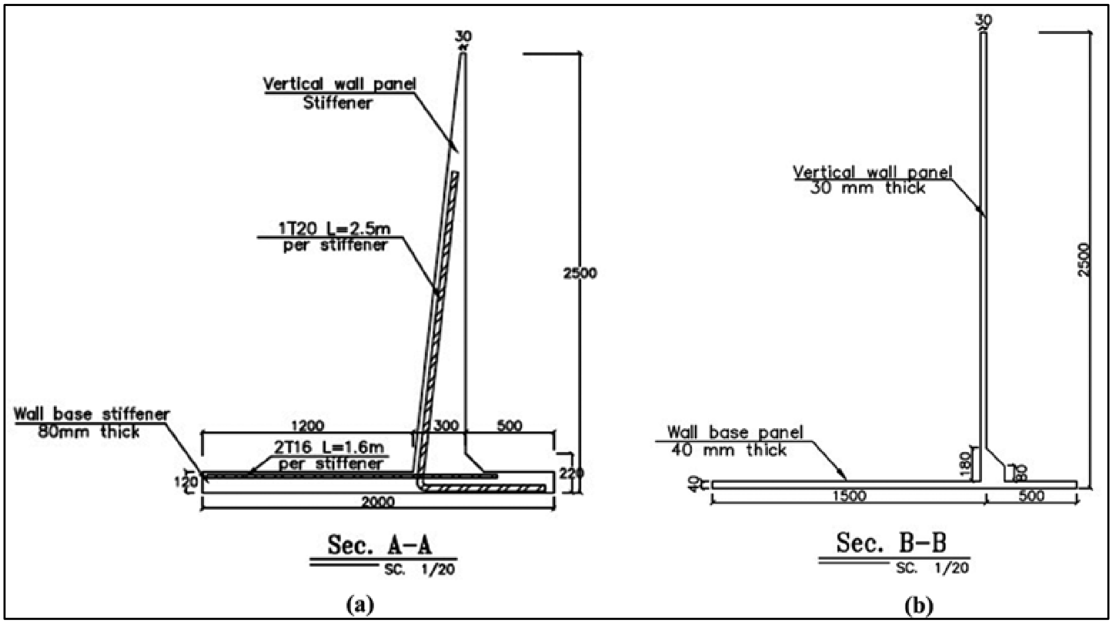


Figure 3. (a) Section A-A and (b) Section B-B of precast UHPC cantilever retaining wall

Table 1. M_{Rd} and M_{Ed} of different critical cross sections of the UHPC wall

Critical UHPC wall cross section	M_{Rd} per specimen length; (kN.m/2 m)	M_{Ed} per specimen length; (kN.m/2 m)
Wall Stem	98.8	60.5
Wall Heal	36.7	28.9
Wall Toe	-24.2	-9.5

3. Environmental Performance Evaluation of Precast UHPC Cantilever Retaining Wall

Environmental performance of the precast UHPC wall is compared against the “conventional” precast RC cantilever retaining wall in terms of material consumption, CO_2 emissions, embodied energy (EE) and 100-year global warming potential (GWP). In this regard, a “conventional” RC wall is analyzed and designed based on Eurocode 7-Geotechnical Design (BS EN 1997-1, 2004) and Eurocode 2-Design of concrete structures (BS EN 1992-1-1, 2004) requirements, respectively. The soil, GWT and loading conditions of the “conventional” RC wall are identical as those of the precast UHPC wall. It should be noted that according to Murthy (2003), the minimum thickness of the “conventional” RC wall stem and the minimum batter should be 300 mm (11.81 in.) and 1:48, respectively. In addition, similar to the UHPC wall, the minimum heel length required to develop the conjugate failure planes should be 1.44 m (4.72 ft.). Therefore, the counterpart “conventional” RC wall has dimensions of 1 m (3.28 ft.) in length, 2.35 m (7.71 ft.) in width, and 2.5 m (8.2 ft.) in height. The dimensions and details of the flexural reinforcement of the “conventional” precast RC wall are presented in Figure 4. The environmental data required for material sustainability evaluation is presented in Table 2.

The material quantities and environmental performance evaluation of each wall are summarized in Table 3. Comparison of the environmental performance of the two walls based on 100% for the “conventional” RC wall is presented in Figure 5. As can be seen, the material consumption and environmental footprints of the proposed precast UHPC wall are significantly lower than those of the "conventional" RC wall. The precast UHPC wall consumes 86% less material and requires 57% less EE for its production compared to the "conventional" precast RC wall. In addition, the construction of precast UHPC wall emits 60% less CO_2 and offer 61% reduction in terms of 100-year GWP compared to the "conventional" precast RC cantilever retaining wall. It should be noted that the savings reported in Figure 5 are only based on the production of the precast UHPC wall specimen, and the additional savings in terms of the foundation, transportation and installation costs are excluded.

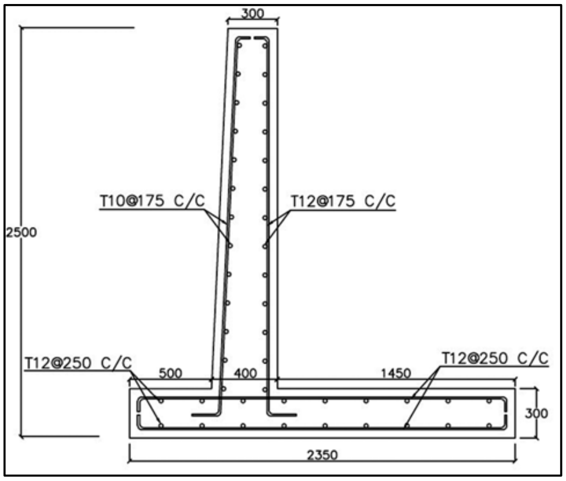


Figure 4. Dimensions and details of conventional precast RC cantilever retaining wall

Table 2. Environmental data used for environmental performance evaluation

	Unit	DURA®-UHPC[1]	Grade-30[2]	Reinforcement
Density	kg/m^3	2350	2350	7840
EE	GJ/ m^3	6.814	1.73	185.8
CO_2	kg/m^3	982	297.5	17123
100-yr GWP	kg CO_2 eq./m^3	2449	795	34392

[1]Environmental values include 1.5% steel fiber contribution.
[2]Conventional concrete containing 15% fly ash, with compressive strength of 30 MPa.

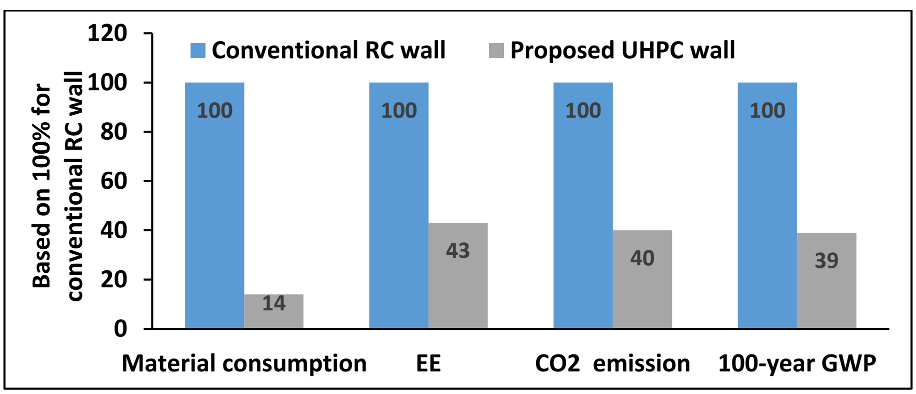


Figure 5. Environmental Performance Comparison of the UHPC Wall vs. "Conventional" RC Wall

Table 3. Material Quantities and Environmental Performance Evaluation of the UHPC Wall

Design method		UHPC[1] (m^3)	Grade 30 (m^3)	Reinforcement (kg)	Total
Conventional RC wall	Grade 30 concrete	0	1.47	0	--
	Steel bars	0	0	70.8	--
	Mass of materials used; (kg)	0	3454.5	70.8	3525.3
	EE; (GJ)	0	2.54	1.68	4.2
	CO_2; (kg)	0	437.3	154.3	591.6
	100-yr GWP; (kg CO_2 eq.)	0	1168.7	310.8	1479.5
UHPC wall	UHPC	0.208	0	0	--
	Steel bars	0	0	14.65	--
	Mass of materials used; (kg)	488.8	0	14.65	503.5
	EE; (GJ)	1.42	0	0.35	1.8
	CO_2; (kg)	204.3	0	31.9	236.2
	100-yr GWP; (kg CO_2 eq.)	509.4	0	64.3	573.7

[1] The UHPC mix design includes 1.5% steel fibers.

4. Construction of Precast UHPC Cantilever Retaining Wall

4.1. UHPC Materials and Mix Design

The UHPC mix design used in construction of the precast UHPC wall is given in Table 4, which is patented under the trade name of DURA®. The ingredients of the DURA®-UHPC premix are Tasek Type I ordinary Portland cement manufactured in Malaysia, densified silica fume with reported particle size range of 0.1 to 1 μm (3.94×10^{-6} to 3.94×10^{-5} in.) and surface fineness of 23700 m^2/kg (115713.5 ft^2/lb), which contains more than 92% of silica dioxide (SiO_2), and washed-sieved fine sand from a local supplier with a particle size range between 100 to 1000 μm (0.004 to 0.04 in.). Two types of steel fibers are used in the UHPC mix design. Type I steel fibers are straight 20 mm (0.79 in.) long by 0.2 mm (0.08 in.) diameter and fabricated from very high strength steel with a tensile strength of 2500 MPa (363 ksi). Type II steel fibers are end-hooked 25 mm (0.98 in.) long by 0.3 mm (0.012 in.) diameter with a very high tensile strength of 2500 MPa (363 ksi).

Table 4: UHPC mix design

Ingredient	Mass (kg/m^3)
DURA®-UHPC Premix	2100
Superplasticizer	40
Steel Fiber (Type I)	60
Steel Fiber (Type II)	60
Free Water	144
3% Moisture	30
Targeted W/B Ratio	0.15
Total Air Void	< 4%

4.2. Mixing, Curing and Casting of Precast UHPC Cantilever Retaining Wall

All dry ingredients are pre-batched appropriately and transferred to a high energy mixer. Water and superplasticizer are added gradually until the materials are uniformly mixed. In the final step, steel fibers are introduced, dispersed uniformly and mixed with the UHPC matrix for a further five minutes. The visual observation indicates that dispersion of the fibers is uniform and there is no evidence of fiber balling. Flow table test, as per ASTM C230M (2008), is conducted before casting of the UHPC wall specimen and the flow values of 200 mm to 220 mm (7.87 to 8.66 in.) after 20 drops of the flow table are achieved. Compressive and flexural strengths of the UHPC mixture are measured experimentally using 100 mm cube specimens and prisms with the dimensions of 100 mm (4 in.) × 100 mm (4 in.) × 500 mm (20 in.), respectively in accordance to relevant standards. Average compressive strength and modulus of rupture of the UHPC mixture after 28 days of ambient temperature curing are determined to be 150 MPa (22 ksi) and 27.4 MPa (3.97 ksi), respectively. Details of the mechanical testing can be found in Nematollahi et al. (2014c).

For casting of the full scale UHPC wall specimen, a steel mold is designed in accordance with the wall drawings. Different views of the steel mold used in this study are presented in Figure 6. The steel mold is cleaned and greased to ease the de-molding procedure. Based on the details of the wall specimens (Figures 2 and 3), the steel reinforcements are installed in the appropriate locations of the mold. The fresh UHPC mixture is poured into the mold and compacted using external vibrators attached to the back and front faces of the steel mold, as shown in Figure 6-(b). The specimen is de-molded 24 hours after casting, and air cured for 28 days. Different views of the UHPC wall specimen after de-molding are presented in Figure 7. Experimental tests using full scale wall specimens are conducted to ascertain the structural reliability of the proposed precast UHPC wall. According to the experimental results, the UHPC wall exhibits superior performance in all aspects compared to the "conventional" precast RC cantilever retaining wall. Details of the full scale experimental testing can be found in Nematollahi et al. (2014c).

5. Advantages of Precast UHPC Cantilever Retaining Wall

The precast UHPC wall proposed in this study offers several advantages compared to the "conventional" precast RC wall. As shown in Table 3, the UHPC wall weighs only 503.5 kg/m (338.3 lb/ft), whereas the "conventional" RC wall weighs 3525.3 kg/m (2368.9 lb/ft). In other words, the UHPC wall is seven times lighter than the "conventional" RC wall. The standard length of the precast UHPC wall is thereby 2 m (6.56 ft.), thanks to its significantly lighter weight; whereas the standard length of the "conventional" precast RC wall is usually 1 m (3.28 ft.). In addition, the precast UHPC wall does not need heavy lifting and installation machineries due to its lighter weight, thereby offers further savings in terms of transportation cost and installation time. Furthermore, the significantly lighter weight of the precast UHPC wall also results in smaller foundation, thereby offers additional savings. According to Figure 5, the precast UHPC wall immediately reduces the consumption of non-renewable raw material (such as aggregate, sand and cement), and in return reduces the CO_2 emissions, EE and 100 year-GWP. In other words, the precast UHPC wall is a green structural member which supports the concept sustainable development. It should be noted that as can be seen in Figures 2 and 3 no secondary reinforcements and crack control bars are used in the UHPC wall. In addition, as shown in Figure 3 no reinforcement is required in the compression face of the UHPC wall stem. Thus, as shown in Table 3, the total weight of the reinforcement used in the UHPC wall is five times less than that of the "conventional" RC wall.

Figure 6. (a) Top view, (b) Front view, and (c) Side view of steel mold

Figure 7. Back view (left), front view (middle) and side view (right) of precast UHPC retaining wall specimen

The precast UHPC wall is volumetrically stable due to negligible creep and shrinkage of UHPC (Voo and Foster, 2010). The precast UHPC wall has a better quality and is aesthetically pleasing as its finishing surface is smooth compared to the "conventional" RC wall. The UHPC wall is mainly suitable for use in extremely aggressive environment such as marine environments or chemically active plants, due to superior durability of UHPC compared to the conventional concrete (Ng et al., 2011; Voo and Foster, 2010; Xie et al., 2008). In addition, the UHPC wall requires almost no maintenance during its service life, thanks to its superior quality and durability compared to the "conventional" RC wall, thereby provides immediate saving in terms of repair and rehabilitation's cost. Thanks to the longer service and design life of the precast UHPC wall, it delays new project to replace the existing structure, which requires consumption of new raw materials, new project cost and public interruption due to construction (Ng et al., 2011; Voo and Foster, 2010). The total life cycle cost (i.e. the total sum of the primary and the maintenance costs) of the precast UHPC wall is less than the "conventional" RC wall (Ng et al., 2011; Voo and Foster, 2010), which provides further savings.

6. Conclusions

A precast UHPC cantilever retaining wall with superior performance to "conventional" precast RC cantilever retaining wall, yet with added advantage of significantly lower environmental footprints is designed and constructed in this study. The precast UHPC cantilever retaining wall consists of two integrated thin UHPC slabs, in which each slab is strengthened with two steel reinforced stiffeners in the appropriate locations. The analysis and design of the precast UHPC cantilever retaining wall are carried out in accordance with Eurocode 7-Geotechnical Design requirements and in conjunction with the JSCE recommendations for design and construction of UHPC structures. A "conventional" precast RC cantilever retaining wall with identical soil properties, ground water table and loading conditions is also analyzed and designed in accordance with Eurocode 7-Geotechnical Design and Eurocode 2-Design of concrete structures, respectively. The environmental performance of the precast UHPC cantilever retaining wall is compared against the "conventional" precast RC cantilever retaining wall. The results indicate that the precast UHPC cantilever retaining wall offers significant savings compared to the "conventional" precast RC cantilever retaining wall with respect to the primary material consumption, embodied energy, CO_2 emissions and global warming potential. The precast UHPC cantilever retaining wall proposed in this study is seven times lighter and requires five times less steel reinforcement than the counterpart "conventional" precast RC cantilever retaining wall. In addition, the proposed precast UHPC cantilever retaining wall offers additional savings in terms of foundation size, transportation cost and installation time, thanks to its significantly lighter weight. The precast UHPC cantilever retaining wall is expected to promote sustainability of the infrastructures via concurrent improvements of material greenness and infrastructure durability.

7. References

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