**Kaohsiung Circle Line LRT – Geotechnical Analyses, Testing and Construction**

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**Abstract**:

Kaohsiung Circle Line Light Rail Transit is an above- ground rail project which is under construction in Kaohsiung City in southern Taiwan and some innovations have been adopted for geotechnical analyses, testing and construction in the project. First, embedded track slab was adopted and top of track is almost at the same level with ground or road surface level which would not lead to any obstacle above ground. However, the whole network is mostly laid on soft alluvium deposit and said system allows very limited displacements of track slab. It is thus difficult to repair if any excessive settlement occurs as the whole track slab is embedded in the ground once the project is open for public operation. By these reasons, various soil improvement schemes, such as replacement of aggregates, pre- consolidation, mechanical soil- cement mixing and soil- cement mixing piles are adopted to reduce possible settlement. In order to achieve the aim of sustainable development, re-use material named “blast air- cooled furnace slag (BACFS)” which comes from waste of iron manufacture is also used as subgrade material to stiffen the ground and details of its properties and performance are presented in this paper.

**Keywords:** embedded track slab, soft alluvium deposit, settlement and tilting of track slab, soil improvement, air- cooled furnace slag

**1. Introduction**

Kaohsiung, which has a population of approximately 2.7 million, is the political and economic centre of southern Taiwan. However, the city is limited by a very poor public transportation infrastructure, and thus, most people must rely on cars and motorbikes for daily transportation.

After completion of two metro lines, Red Line and Orange Line, it has a need to construct additional metro or light rail lines to connect two metro lines stated above in order to allow passengers to be transferred in anywhere in the city easily. Therefore, it thus has a concept to build a circle metro/rail line system to connect existent metro and train lines so Kaohsiung Circle Line Light Rail Transit (LRT, or be named “tramway”) is thus constructed.

In this paper, it aims to examine and discuss some details of geotechnical design, testing and construction of Kaohsiung Circle Line LRT project. Some innovation works in this project will be reported also.

**2. Project Background**

Kaohsiung Circle Line LRT project is the 1st catenary-free power supply system LRT/tramway in Asia. Construction of the whole project is divided into two phases: Phase 1 with route length of 8.7 km including 14 stations, one substation and one depot was launched for construction in 2013 and was open to public operation in 2017. Figure 1a presents the overall network of Kaohsiung Circle Line LRT and also indicates the location of Phase 1 stretching from C1 to C14 Station. The whole main line, stations and depot were constructed on surface of Phase 1 and only two bridges have to be built for canal and river- crossing.

The location of Phase 2 is presented in Figure 1a as well. The network of Phase 2 is even longer which has 13.4 km long with 22 stations. Similar to Phase 1, all construction activities of main line and stations are delivered on surface level except some bridges constructed for large- scale culvert crossing.

Once both Phase 1 and Phase 2 of Kaohsiung Circle Line LRT are completed, the network is anticipated to connect with both existent Kaohsiung Metro Red and Orange Line as well as TRA railway in order to provide a better public transportation of the city (Refer to Figure 1).

Considering details taken from some representative boreholes at several locations along the route, as indicated in Figure 2, it is aware that the unit weight of soil varies in the range of 17.5 to 21 kN/m3, natural water content changes from 10 to 30% and in- situ void ratio is in the range of 0.7 to 1.2. SPT- N value is less than 20 for ground within 20 m from surface level. It is recognised that the LRT project has to be mainly laid on 10 meters or even more soft alluvium deposit but ground variance is observed at different locations. As shown in Figure 2a, a thicker clayey material is found in section between C14 to C18 Station but similar material is not seen in the corridor of old East Harbour Line (C32 to C36 Station), as presented in Figure 2b. Groundwater level varies from surface level to 5 m below surface level and it is highly affected by tidal influence in the coastal area.

In order to further understand ground condition, especially in coastal area, cone penetration test (CPT) were delivered in order to understand cone resistance (Qc) and friction force (fs) of soils. Test results are presented in Figure 2c. It is thus aware that measured Qc is up to 8 to 12 MPa and fs could reach to up to 60 to 70 kPa, respectively. Very stiff ground was found at approximately 1 m below surface level in several locations near the coast, as shown in Figure 2d and it is anticipated that might be connected with coral reef in the ground.

**3. Challenge in Use of Embedded Track Slab**

In addition to a special and unique catenary -free arrangement of power- supply system to the tram in order to provide a better city view and skyline in the aspect of the system, a special requirement of the use of embedded track slab is also requested by the project owner in this project. In order not to make any obstacle on ground surface, an innovation here is the track used for tramway operation is embedded in track slab and there is no sleeper in the track system so top of track can remain almost the same level with ground level which is different with other rail or metro systems. Figure 3a presents a typical cross section of embedded track slab system and Figure 3b shows construction sequence of track part of tramway. Figure 3c presents tram operation on the road. It is noticed from Figure 3 the track is fully embedded inside the slab and again the slab is fully embedded in the ground or road so track- level can be fully lower than ground level and doesn’t have to cause any obstacle on the ground. Except advantages stated above, the use of embedded track system could possibly reduce noise and vibration induced by train operation (Esveld, 2010; Gailienė and Laurinavičius, 2017; Balfour Beatty, 2018). Therefore, said system has been adopted in several cities in Europe. However, challenge of said track system is both of track and slab are deeply embedded in the soils and it is difficult to repair once there is any excessive tilting/settlement induced during tram operation stage. It is thus aware that special subgrade material/treatment have to be adopted before track and track slab are constructed, especially the whole network is almost laid on soft alluvium deposit. This thus becomes an important issue for geotechnical design, testing and construction of the project and also ***a unique innovation*** which this paper would like to address.

**4. Soil Improvement Scheme**

As described above, the track slab was laid on soft alluvium deposit in Kaohsiung Circle Line LRT so subgrade has to be strengthened in order to fulfil requirement of settlement and tilting of track slab. Generally the procedures of plate load test (PLT) stated in DIN18134 (2012) has to be followed and strain modulus, EV2, has to be interpreted from results of PLT and EV2 of subgrade layer has to be greater than 80 MPa associated with system requirement given by project owner. Further, differential settlement of track slab has to remain less than 2 mm for every 3 meters based on requirements stated in UIC 776-2R (2009). In addition, ground and neighbourhood environment do have certain variances so different protection measures shall be considered. Therefore, various soil improvement schemes are adopted. Tsai et al. (2014) did propose some possible methods, such hot-mix asphalt or thicker plain concrete layer and Table 1 lists soil improvement scheme at different sections applied at the end and details are described, as follows:

Refer to Table 1, the 1st improvement scheme is to simply replace the original soils to aggregate due to a better ground condition beneath track slab.　After that, replacement of 0.5 thick compacted aggregate material, pre- consolidation and installation of stone column are adopted together in order to provide adequate ground strength and stiffness to prevent excessive settlement and tilting of track slab caused by later tram operation. As shown in Figure 4a, it presents a typical cross section of stone column installed on site. Figures 4b and 4c show site construction sequence and activities of stone column as well as particle size used for stone column and Table 2 details overall construction sequence of soil improvement here. However, due to constrains of construction of road junction using methods stated above since time for junction closing and traffic diversion has to be as short as possible, it is thus decided to lay 21 MPa (28- day curing period) of unconfined compression strength of concrete as base material beneath track slab directly.

For section between Chen- Kung Bridge and Love River Bridge, 50 cm thick mechanical soil- cement mixed material (refer to Figure 5 for details of site activities and construction sequence) was used as a subgrade soils and again 50 cm thick compacted aggregate was laid on top of mechanical soil- cement mixed material.

For the section moving further toward the coastal area, the ground becomes softer so an additional improvement measure has to be considered. Soil- cement mixing piles were installed into certain depth in order to provide adequate ground strength and stiffness, except controlled low strength material (CLSM) or low strength plain concrete laid beneath track slab. Lin and Wong (1999) concluded that additional heavy loading on top of soft alluvium deposit, such as road embankment could lead significant settlement but the use of soil- cement mixing piles might reduce said settlement. Figure 6 presents schematic drawing of representative layout and cross section as well as site activities of this soil improvement scheme.

For Phase II (starting from tail track next to C14 station), soil improvement scheme has been changed again. In order to strength the soils, blasted air-cooled furnace slag (BACFS) is used to form a function of rigid foundation and also replace granular materials. Details and requirements of BACFS will be described in later section. However, ground at some locations are particularly weak (soft clay with SPT-N value less than 4) so it has to be strengthened after evaluation, except the use of BACFS. Therefore, similar to Phase 1, two parallel rows of soil- cement mixing pile with 1 m of diameter, 6 m of the length were installed in the ground below the layer of BACFS.

**5. Alternative Subgrade Materials- Blasted Air- Cooled Furnace Slag**

In order to achieve the purpose of sustainable development, recycle/waste material shall be re- used if there is any chance. Therefore, blasted air- cooled furnace slag (BACFS) is proposed by the contractor to be alternative subgrade materials to replace aggregates or even low- strength concrete which is also the other ***innovation*** in this project since such material never been used for any rail or metro project previously and some fundamental properties of BACFS were reported by Wang (2014).

During the processing of iron manufacture, BACFS are produced as a waste. In order to achieve the purpose of sustainable development and re- use of waste, BACFS is thus considered to replace aggregate and other materials having similar function. Through various manufacture process, different types of BACFS are made and Type MS-40 of BACFS is selected for construction of subgrade of track slab. There are several requirements which BACFS has to fulfil, such as particle distribution, stability of volume (expansion) and minimum strain modulus of subgrade after BACFS has laid has to be satisfied.

Figure 7a presents Type MS-40 used and also its size of particle distribution and Figure 7b present stress- strain curve from unconfined compression tests for different ageing periods. It indicates the unconfined peak strength of BACFS is in the range of 1600 to 2300 kPa and secant line stiffness at peak is in the range of 88 to 175 MPa which will be compared with outcomes from numerical simulation later. It is noted from Figure 7b too that both ageing period and water content could possibly affect BACFS strength and stiffness. Again, due to stress- strain relationship, strain level at failure and cementation of the material, it is recognized as a semi- concrete type material instead of soil. Results from expansion tests also shows that there is almost “zero expansion” of BACFS which release the concern of damage of track slab caused of expansion of BACFS (refer to Figure 8a). Figure 8b shows the construction of subgrade using BACFS and at the end that 30 cm thickness of BACFS together with 40 cm thick of track slab are decided to be constructed on site after several optimised evaluations.

**6. Testing and Three- Dimensional Numerical Analyses**

In order to further confirm the effectiveness of soil- cement mixing pile, additional non- destructive testing (NDT) was conducted at several locations. The NDT selected is named “multichannel analysis of surface wave (MASW)” and previous literature about the use of MASW can be referred to Park et al. (1999), Xia et al. (2002) and Cheng et al. (2016). Equipment of MASW shall include a vibration source, receivers and data log which used for storage of data. In general, vibration was made first and shear wave velocity of soils at various depths were received via receivers on surface level. By doing so, the shear modulus of soil can thus be interpreted associated with shear wave velocity measured.

Results of MASW from two selected sections are presented and discussed in this paper. The soil improvement scheme here is to install 60 cm of diameter soil- cement mixing pile and the interval between 2 piles is 3.4 m in transverse direction and 1.85 m in longitudinal direction. The depth of pile toe is 7 m. 1.5 m to 2.5 m thick of CLSM was laid beneath track slab (on top of piles), depends on strength of original soils in the ground.

For testing itself, two test lines were arranged: one was laid on top of soils between two piles and the other was laid on top of soils outside construction area in which soils are expected to be original one and not affected by any activity of soil improvement at all.

Figure 9a presents shear wave velocity (Vs) measured from location having chain- age at 7k+505 to 7k+ 528. For soils without any improvement (original soils), Vs varies between 100 m/s and 150 m/s for ground having the depth from surface level to 4 m below surface level and then gradually increases to 200 m/s to 10 m below surface level. In contrast, Vs remains 150 m/s from surface level to 5 m below surface level and then gradually increases to 200 m/s. Considering results from MASW, it is approved that even soil could not be fully improved, soil- cement mixing piles installed on site also have certain impacts on adjacent ground which also stiffen soils and then expect to reduce settlement of track slab once tram starts to operate.

Figure 9b presents Vs profile from additional test lines located at centreline between two soil- cement mixed piles in other places near and it is aware that Vs can still reach 150 m/s the minimum after the soils were improved and the maximum value can reach up to 350 m/s. It is aware that the groundwater level is approximately at 1.5 m below surface level. Said results can be presented in 2- dimensional drawing in terms of ground depth and chain-age, as shown in Figure 9c. It is also concluded that interpreted soil shear modulus shall be in the range of 42.75 MPa to 232.75 MPa which is in a comparatively large range. This also implies that effectiveness of the use of soil- cement mixing piles could be very various.

To further confirm elastic modulus of BACFS and also induced settlement of track slab, three- dimensional numerical analyse were thus planned and conducted. The 1st task is to validate elastic modulus of BACFS through results of PLT and the other task aims to understand immediate settlement caused by future tram operation.

The finite element method (FEM) software PLAXIS3D version 2016, made in Delft, Netherland was selected as a tool of inverse analyses. Figure 10a and Figure 10b shows in- situ PLT, model used for analyses of PLT and dimensions of model is 74 m × 30 m × 10 m. As mentioned above, BACFS is recognized as a semi- concrete type material associated with its failure strain level and mechanism so a linear elastic model is chosen for the simulation of behaviour of BACFS. In addition, the same constitutive model is taken as the plate of PLT in terms of its thickness and adjacent ground. It is anticipated that limited displacement shall occur during the testing so the model with small strain characteristic named “Hardening Soil- small strain (HSS)” is selected for simulation of ground behaviours.

For PLT simulation, vertical load applied was added which is exactly the same with the load applied in PLT for inverse analyses in which real displacements from PLT are taken as target values. 30 cm, 40 cm and 50 cm of thickness of BACFS was laid on top of original ground. Considering results from inverse analyses, elastic modulus of BACFS is in the range of 140 MPa to 200 MPa which is similar to results obtained from unconfined compression test.

After completing the inverse analyses of PLT, possible settlement of track slab was simulated. The software PLAXIS3D is again chosen for settlement evaluation. Figure 11 shows dimensions of the model which is similar to the one used for inverses of PLT. The decision of width of the model is considered based on previous study conducted by Shih (2016) and the boundary has to be far enough which not affected by any additional loading is added on the track slab and model depth is defined based on depth of borehole which can provide available soil information. For the length of model, it is mainly associated with the length of tram and adequate length shall be left in the front and back of tram in longitudinal direction and similarly, any activity in the model shall not induce extra displacement and stress at boundaries. A 5.9 m wide, 74 m long, 0.4 m thick track slab using linear- elastic element for simulation was put at centreline of the model. Moreover, linear- elastic elements with dimensions of 0.3 m thick, 5.9 m wide and 74 m long are installed between slab and soils in the model to simulate behaviour of BACFS. Though it is aware that elastic modulus of BACFS shall be at least up to 88 MPa for 7- day aging period from laboratory test results and said value shall increase once aging period is longer, it still assumes 80 MPa of elastic modulus of BACFS based on details given in construction specification. Further, due to availability of soil parameters and comparatively larger displacements caused by tram operation rather than PLT, a constitutive model named “Hardening Soil” is selected for soils instead of HSS model.

Two locations with soft alluvium deposit ground on main line (not station area) are chosen as background site for evaluation of immediate settlement caused by tram operation. Lichtberger (2011) indicated that a slower speed train should increase settlement so the scenario is assumed trams on both up-line and down-line were passing at the same location and pseudo dynamic force is considered in order to simulate dynamic impact. Therefore, six 81.9 kN of point load, equivalent to load on each wheel of tram were applied on single track which is equivalent to the same loading from one tram on one track. Figure 12 presents immediate settlement contour caused by tram operation and it shows that the maximum immediate settlement is less than 3 mm.

Except immediate settlement, Heukelom and Klomp (1962) mentioned tram operation could bring cyclic loading so additional check for allowable soil stress beneath subgrade material under cyclic loading induced shall be conducted. In addition, accumulated plastic displacement induced by both plastic strain (Li and Selig, 1996) and consolidation settlement of clayey materials shall be calculated as well. Extra analyses about items stated above were thus delivered and it is recommended that the sum of settlements is over 25 mm in certain locations between C14 and C18 station so additional soil improvement measure, such as soil- cement mixing piles indicated in previous section shall be carried out in order to reduce the settlement to an acceptable level.

**5. Conclusions**

In order to further improve public transportation of the city, Kaohsiung Circle Line LRT which is 22 km long with 36 at- grade stations are constructed. In this project, embedded track slab which can remain top of the track at almost the same surface level of road is applied which is an innovation since no obstacle on surface level was made by rail. However, it is difficult to repair said track if any excessive settlement occurs which brings a challenge to geotechnical analyses, testing and construction of the project. Due to the constrain of settlement requirement and soft ground condition, various soil improvement schemes are adopted, such as stone column, pre- consolidation, CLSM and mechanical soil- cement mixing/soil- cement mixing pile which are capable to strengthen the ground.

From the view of sustainable development and use of recycle materials, BACFS were used as subgrade of track slab and it could be possibly control the settlement of track slab within allowable value. This is also the 1st time that BACFS is used as subgrade material of rail project.

Additional in- situ NDT named MASW was applied to evaluate soil stiffness and also performance of soil improvement. Though outcome of evaluation of MASW, it is aware that though the diameter of soil- cement mixing pile is comparatively small, it does bring certain level of influence in the aspect of strengthening of ground.

At the end, 3- dimensional analyses were conducted in order to confirm behaviour and stiffness of BACFS from PLT and also evaluation possible immediate settlement of track slab caused by tram operation. It is concluded that BACFS is a semi- concrete material and its stiffness is consistent with results from laboratory tests. For tram operation, it shall consider both immediate and plastic settlement and necessary soil improvement scheme shall be considered if the sum is above accepted level.

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