A REVIEW ON LATERAL RESPONSE OF DCM AND A CASE STUDY

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Abstract - Deep cement mixing (DCM) is one of the geotechnical solutions to support an embankment. The horizontal bearing capacity of the DCM is insufficient to resist high lateral loads, which may lead to large horizontal displacements or even failures of the structure. Therefore, the lateral resistance of the DCM material is the main challenge that needs to be studied in depth. Lateral resistance improvement methods, such as using steel beams, concrete piles, T-shape columns, fibres, anchors, and PVDs, are presented based on previous research. A case study at the Hiep-Phuoc Container port project in Vietnam is used to analyse failure reasons and recommendations provided.

Key words - Deep cement mixing; lateral resistance; embankment; improvement methods; case study.

1. Introduction

Deep mixing method (DMM) is an in-situ soil treatment method in which native soils or fills are blended with cementitious or other stabilising agents (binder) [1]. Materials such as cement, lime, slag, and fly ash are commonly used as stabilising agents [1]. This method was developed in 1967 to increase the stability of foundations (in Japan), reduce settlement, and increase the stability of embankments (in Sweden) [1-4]. Since the 1980s, DMM has been applied widely in Japan, Europe, China, Singapore, Hong Kong, and America, with more than 100 million m^3 of soil stabilised in over one thousand projects [1, 3, 5]. In Vietnam, DMM has been used recently in ground improvement and foundations. DMM includes dry and wet mixing (jet grouting), which requires more cement content than the dry mixing method [6]; however, it provides higher average strength [6].

The advantages of DMM include economics, flexibility, savings of materials and energy by exploiting the properties of the soil at the site, producing only small vibrations and low construction noise, with low costs and rapid installation [1, 4, 5, 7]. However, it has a limitation in terms of column length, final bearing capacity, and lateral resistance [8].

DCM can be applied as the foundation of various structures such as earth retaining wall structures, foundations, soil reinforcement, land levees and floodwalls stabilisation, remediation, barrier against liquefaction, embankments, excavation walls, reinforcement piles, breakwaters, and high-rise buildings [1, 9-11]. For some structures, DCM needs to resist the lateral loads from earth pressure, water and tide pressure, landslides, or earthquake loads. By applying DCM, the lateral resistance of the embankment structures could be increased from 60% to 260% [6]. However, the horizontal bearing capacity of DCM is insufficient to resist high lateral loads, which may lead to large horizontal displacements or even failure of the structure. To support the embankment or retaining structures, the lateral resistance of DCM could be enhanced by using steel beams, concrete piles, T-shape columns, PVDs, or fibres [3]. This paper presents previous studies on the lateral response of deep cement mixing material.

2. DCM support for embankments

A popular application of DCM materials is to support embankments, as embankment construction on soft soil could be subject to tensile failure, shear failure, bending moment, or side slope failure [12]. A typical section of embankment reinforced by a DCM column is shown in Figure 1.

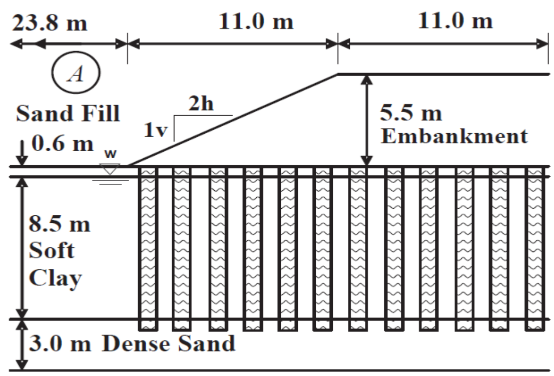

Figure 1. *Embankment supported by a deep cement mixing column [12]*

In addition, in some cases, the embankments and pavements need to be widened to increase transportation capacity, which then could lead to differential settlement or slope failure due to soft ground. Han, et al. [13] showed that the soil-cement column (SCC) reduces not only total settlement and differential settlement of widening embankment, but also reduces lateral displacement of the system (Figure 2).

Furthermore, physical models, centrifugal tests, and numerical models have also been applied to analyse the effect of DCM columns to stabilise embankments. One of the technical aspects of an embankment supported by a deep mixing column is lateral resistance. For DCM materials, compressive strength is higher than tensile strength, which means that the system could collapse in the case of high lateral loads affecting the DCM column. There are several methods to improve the lateral response of the

DCM column, such as using prefabricated vertical drains (PVD), T-shape columns, steel beams, and concrete piles.

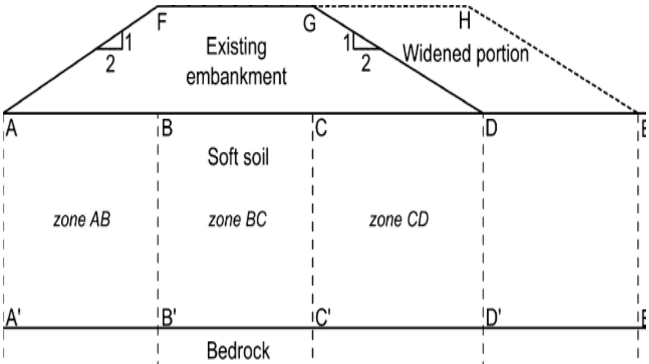

***Figure 2.** Example of a widened embankment supported by the soil-cement column [13]*

Case histories indicate that the settlement of surrounding untreated soil is always higher than soil treated by DCM under embankment loading conditions [14]. The difference in settlement between treated and untreated soils can be as high as 8 to 20% of the average settlement at the ground surface [14].

In 2015, Ye, et al. [15] presented a centrifugal model result on an embankment on a composite foundation combined with SCC and prefabricated vertical drains (PVDs) as presented in Figure 3. As a result, the lateral displacement decreases when the length of SCC is increased, which then leads to an improvement in the stability of the embankment. Besides, SCC transfers the loads to the lower layer, and PVDs can accelerate the consolidation of the soil layer below the SCC system [15]. Moreover, the composite foundation increases the shear strength of the ground and the consolidation rate, as well as decreases the pore water pressure and the settlement over time [16, 17].

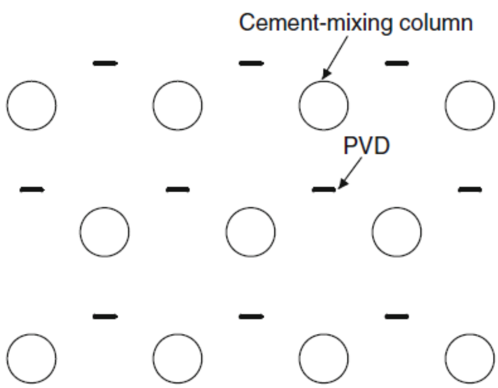

***Figure 3.** The layout of a composite foundation with SCC and PVDs [15]*

To improve the ratio of area replacement, a type of SCC called a T-shape deep mixing (TDM) column has been applied in the field, in which the portion near the surface is opened its diameter, and the deeper part of the DCM column shows a smaller diameter [18] (Figure 4). Using TDM could decrease 67% total settlement of ground, reduce 6.5% of cement and 19% of construction time, as well as decrease 31% lateral movement [18-20]. In terms of lateral displacement of the ground, the maximum lateral movement value of the TDM column is smaller and shallower than conventional SCC [18]. Moreover, the lateral displacement ratio at the embankment centerline of the TDM column is smaller, and its enhancement of the stability of the embankment is better than usual SCC [21]. These researchers have conducted laboratory tests, numerical models by FLAC 3D, and field tests to make the conclusion that the TDM column provides a viable, economic solution and brings more benefits than conventional SCC [21].

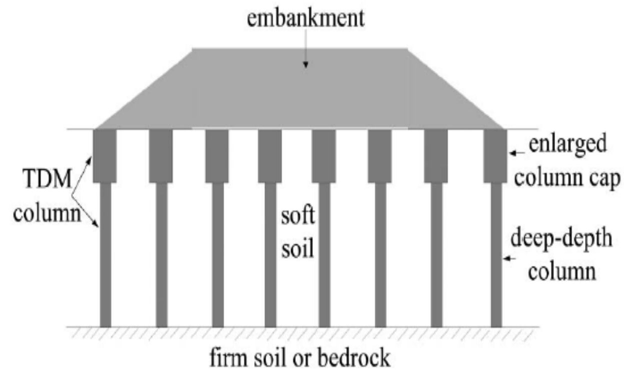

***Figure 4.** An illustration of the TDM column supporting the embankment [18]*

Another solution to improve the lateral resistance of the DCM system is to use concrete piles or steel beams to insert into the centre of fresh soil mixing material. It is known as stiffened deep cement mixing (SDCM) or deep cement mixing bored pile (DCM-BP) [22, 23]. SDCM is a composite structure of a concrete pile or steel beam and DCM column, which then works together by transferring the loads to the surrounding soil. Figure 5 shows an example of the SDCM using a square prestressed concrete pile. The composite structure can resist the shear forces and bending moments from the embankment loads. Hence, it prevents pile failure, soil failure, and increases the stability and bearing capacity of the embankment [17].

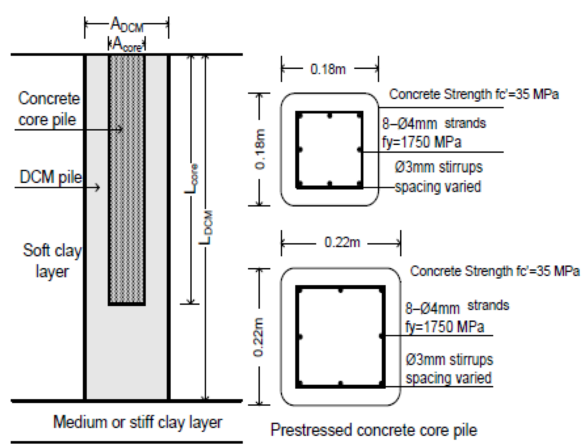

***Figure 5.** Details of the SDCM pile [24]*

In 2013, Raongjant and Jing [25] conducted research on SDCM under lateral cyclic loading, and they found that the SDCM with the H-steel beam core increases lateral resistance capacity 3-4 times. Similar results were shown in the research of Voottipruex, et al. [24], Jamsawang, et al. [26], Wonglert and Jongpradist [27]. They conducted a simulation model by PLAXIS 3D software and compared simulated results to observe data to make the conclusions that the SDCM piles reinforced by concrete core piles increase the bearing capacity by 2.2 times and lateral capacity by 15 times higher than the typical DCM piles. Besides, SDCM resists lateral loads 5.4 times higher than a concrete pile only. So, it could be said that SDCM has a bearing capacity and lateral resistance much higher than conventional DCM and concrete pile, and it is suitable for reinforcing the embankment on soft clay [22].

In the research of Wonglert and Jongpradist [27], they present the principle of the design process, choosing the length and diameter of the core pile, and the simulation method by PLAXIS 3D. In which the clay layer was modelled as the Hardening Soil Model, soft clay and medium stiffness clay were modelled as the Soft-soil model, and the DCM material and sand layer were assumed to behave as elastic-perfectly plastic material, as the Mohr-Coulomb model. They found that by increasing the core length, the bearing capacity of the composite foundation is increased, and the total settlement of the ground is decreased [27]. However, the diameter of the concrete core pile significantly affects the bending capacity of the SDCM pile and the lateral movement of the embankment [17, 24, 27]. In addition, they found that increasing the length of the concrete pile does not increase the lateral load capacity of the SDCM [24]. Furthermore, the SDCM piles increase the skin friction of the concrete piles and long-term strength of the structure, which then enhances the surrounding lateral resistance and the performance of the core concrete piles [22].

Table 1. *Effectiveness of DCM support for embankment*

No.	Method	Improvement Effect	Reference
1	DCM	Stiffness increased by 2–5 times	[3], [4], [7], [12]
2	DCM	Elastic modulus increased from 5 MPa (soft clay) to 25–50 MPa	[8], [13]
3	DCM	Lateral displacement reduced by >50%	[6], [12], [22]
4	SDCM	Stiffness increased by 3–10 times compared to ordinary DCM	[17], [23], [24]
5	SDCM	Lateral load capacity increased by 2–4 times over DCM	[23], [25], [26]
6	SDCM	Lateral displacement was reduced by up to 70% compared to DCM	[24], [27]
7	T-shaped DCM	Ground displacement was reduced by up to 80% compared to untreated soil	[20], [21]

In terms of the durability of SDCM, Denies, et al. [28] shown that the degradation of DCM material with time depends on wet-dry and freeze-thaw cycles, carbonation, diffusion of calcium, sulphate, and chloride attack. Hence, using concrete core piles in the coastal areas could avoid the impact of corrosion on the fresh soil mix material [28].

It is clear that the DCM column improves the stability of the embankment and decreases the lateral displacement of the ground. However, under high lateral loads, the structures need to be strengthened by a combination of concrete piles, steel beams, PVDs, and steel or polypropylene fibers.

Table 1 summarises the effectiveness of DCM support for embankment. In order to understand the behaviour of DCM reinforcement, a case study is presented in the next section.

3. A case study at the Hiep Phuoc container port project in Vietnam

The construction site of the Saigon Premier Container Terminal Project, which is located along the Saigon River, is covered with a thick soft clay deposit. In order to improve the engineering properties of soft clay behind the berth structure, DCM application is used as a wall to reinforce the embankment.

After the 14th loading and dredging of the river, the whole DCM system was damaged. The largest place had a displacement of 11 m. The failure occurred at the project, and the solution, as well as the design experience obtained from the project, are analysed.

3.1. Soil profile

In order to determine the cement content of DCM and the appropriate engineering parameters of subsoil materials, a soil investigation was planned and executed. The soil investigation mentioned here was carried out at the site.

Figure 6 presents the physical and strength properties obtained from undisturbed samples, together with SPT (N) values for the top of the stiff clay deposit and sandy layers. The soil profile includes mainly a soft clay from -3 to -32 m, and stiff clay from -32 to -46 m. In terms of particle size distribution, the soft clay layer contains 60% of silt and 40% of clay.

3.2. Embankment design

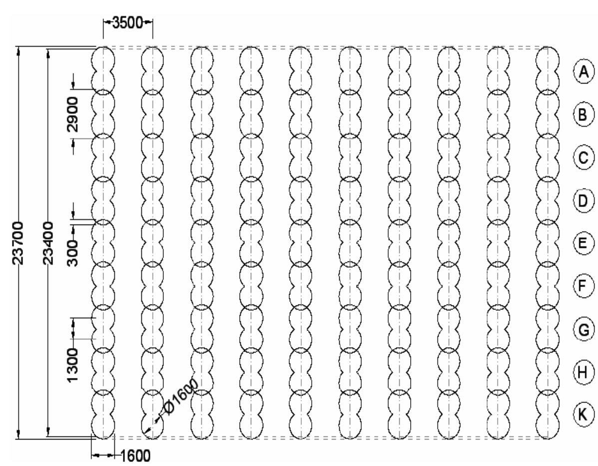

Figure 7. *DCM design*

The surface of the embankment is located at a +3.5 m level. The riverbed along the port needs to be dredged to an excavation of -8.5 m. To reinforce the embankment, the DCM was applied. The DCM wall is composed of D1600 DCM piles (Figure 7). The DCM piles overlap with a section of 300 mm, a wall width of 23.7 m, and a length of reinforcement DCM 950 m. The distance of each wall from the heart was 3.5 m. Cement content was C = 200 kg/m^3, and cement PCB40/PC40 was used. The soil-cement columns were constructed through the soft clay using the wet deep mixing method designed to have an unconfined compressive strength of 500 KPa and, therefore, an undrained shear strength of 250 KPa. The shear strength of the original soft soil was not considered to contribute to the stability. The construction process is shown in Table 1. DCM peak height is + 1.0 m, and DCM bottom elevation is -34.0 m. A construction load of 20 kN/m2 was applied. According to [29], the allowable displacement is less than 0.5% of embankment height, and the safety factor is 1.5.

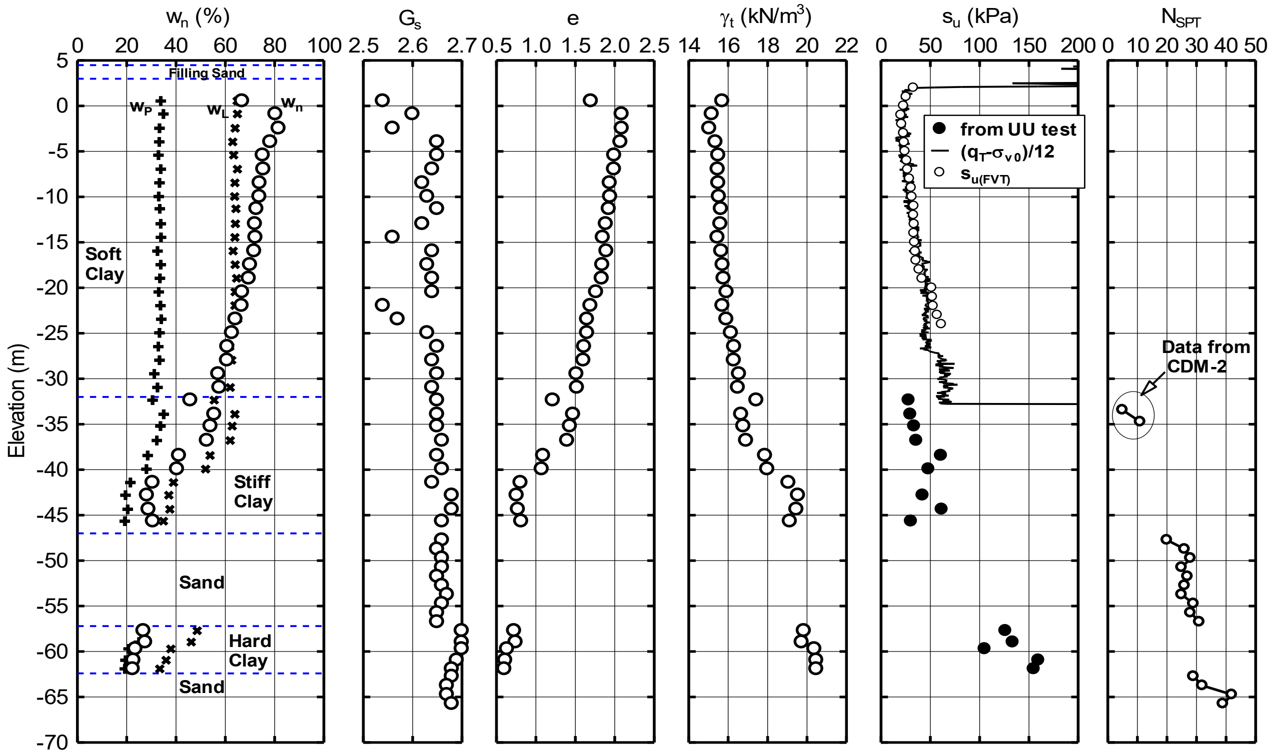

Figure 6. *Physical and strength properties obtained from undisturbed samples*

Table 2. *Construction process*

Phase	Main task
Phase 1	Filling the 1st layer with a thickness of 1m
Phase 2	Filling the 2nd layer with a thickness of 0.5m
Phase 3	Filling the 3rd layer with a thickness of 0.5m
Phase 4	Filling the 4th layer with a thickness of 0.5m
Phase 5	Filling the 5th layer with a thickness of 0.5m
Phase 6	Filling the 6th layer with a thickness of 0.5m
Phase 7	Replacement of sand ground
Phase 8	Filling ground
Phase 9	DCM construction
Phase 10	Filling the 7th layer with a thickness of 0.5m
Phase 11	Filling the 8th layer with a thickness of 0.5m
Phase 12	Filling the 9th layer with a thickness of 0.5m
Phase 13	Filling the 10th layer with a thickness of 0.5m
Phase 14	Filling the 11th layer with a thickness of 0.5m
Phase 15	Filling the 12th layer with a thickness of 0.5m
Phase 16	Filling the 13th layer with a thickness of 0.5m
Phase 17	Filling the 14th layer with a thickness of 0.5m
Phase 18	Dredging of the river bed

3.3. Failure of DCM wall

After the 14th loading and dredging of the river, the whole DCM was observed from the section 650 to 750 damaged as Figure 8.

Figure 9 shows the inclinometer observation before and after failure. It could be seen that the horizontal displacement of the embankment after 5th June was larger than 0.5 m, and the failure seemed to occur at a depth of 5-10 m.

To determine the failure, analysis by Geo-slope in combined with Sigma, and PLAXIS, was conducted. In both models, a soft clay layer was defined as the Modified Cam-clay model. The result shows the safety factor according to Slope-sigma is 0.928, which means that the embankment will fail during the construction process. The PLAXIS result shows that the failure occurred at a depth of 8.5 m when the riverbed was dredged. That result is similar to the inclinometer observation.

To treat the damage, a failed DCM was replaced by cement-mixing soil (CMS). In addition, an H-steel beam was inserted into the DCM to reinforce the DCM block (Figure 10). As mentioned in the previous section, using an H-steel beam core increases lateral resistance 3-4 times. Therefore, it improves the lateral response of the DCM system.

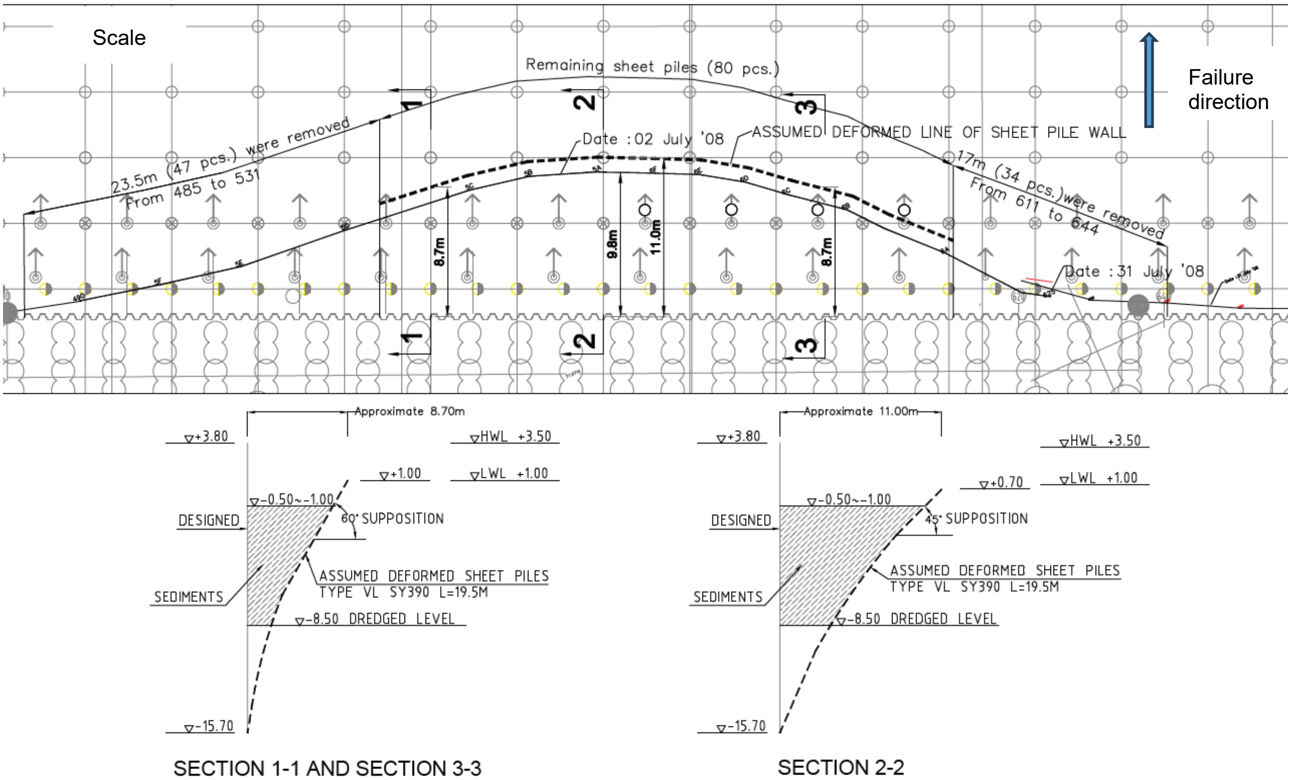

Figure 8. *Failure area*

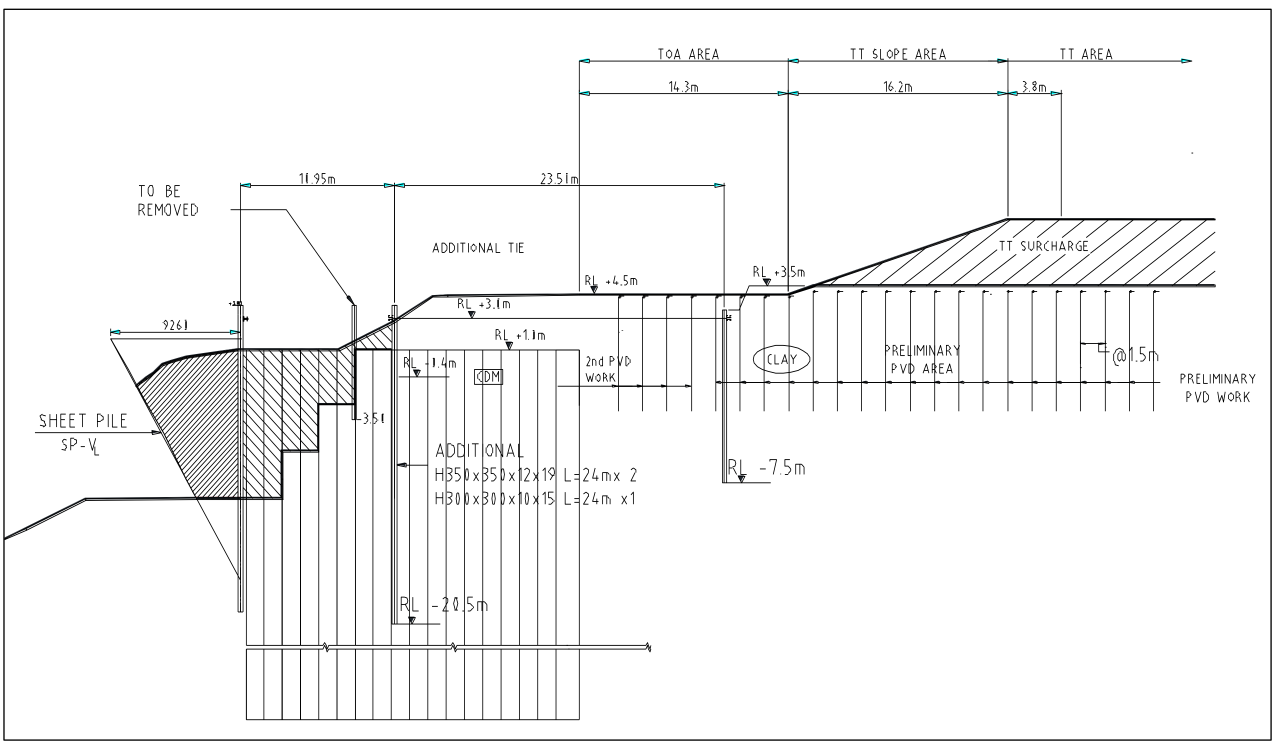

Figure 9. *Treatment solution*

4. Conclusions

It is clear that the DCM column improves the stability of the embankment and decreases the lateral displacement of the ground. However, under high lateral loads, the structures need to be strengthened by a combination of concrete piles, steel beams, or PVDs.

A failure of the DCM wall at Hiep-Phuoc container port under high lateral loads was observed. It is suggested that a reinforcement method should be used to improve the horizontal bearing capacity of the DCM wall. The behaviour of the lateral response of DCM reinforcement under seismic or dynamic loading should be considered for specific conditions.

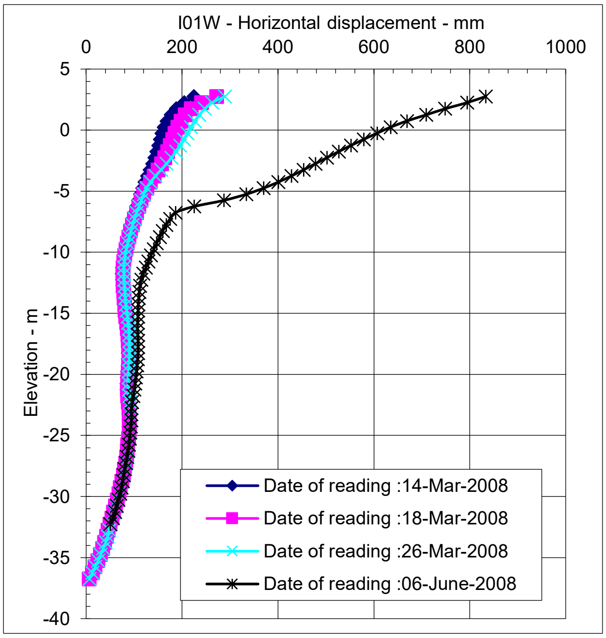

Figure 9. *Inclinometer before and after failures.5*

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