

Experimental Study on Mechanical Properties of In-situ Solidified Soil and Modulus Effect of the Solidified Layer in Composite Foundation behind Bridge Abutments

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Abstract: Shallow in-situ solidification combined with deep cement mixing columns is widely used to control differential settlement behind bridge abutments, yet the mix proportion and stiffness of the solidified layer are still usually chosen by experience. Taking a bridge project in East China as the background, this study tests the mechanical properties of in-situ solidified soil in the laboratory, proposes a mix design method based on the water–cement ratio index, and uses a numerical model to quantify how the modulus and thickness of the solidified layer affect settlement, so that the recommended parameters balance effectiveness and cost. The tests show that the water–cement ratio index — the water–cement ratio divided by the liquid limit — correlates almost linearly with the reciprocal of the unconfined compressive strength (UCS), so soils of different types can be placed in one calibration system; a water–cement ratio of 1.5 is recommended. Strength grows with cement content and curing age (the 14 d value reaches about 80% of the 28 d value) and drops exponentially as the water content rises. Replacing part of the cement with activated mineral powder (6% cement + 2% activated mineral powder) raises the 28 d strength by about 19.3% without lowering the 90 d resilient modulus, so strength and stiffness improve together. The numerical results are less encouraging for simply stiffening the layer: raising the modulus from 60 MPa to 140 MPa cuts the total settlement of the solidified zone by only about 3.3% (less than 1% in the non-solidified zone), whereas each additional metre of thickness reduces it by about 1.68 mm, roughly 5%, which makes the settlement-control efficiency per unit cement consumption about 5–6 times higher. Settlement behind the abutment is evidently governed by the underlying soft clay, and the modulus of the solidified layer is not the controlling variable. In practice, the recommended mix proportion should be used to secure strength and durability, deformation should be adjusted by thickening the layer within equipment limits, and the remaining settlement should be handled through the column parameters.

1. Introduction

1.1 Background

The back of a bridge abutment is a typical rigid–flexible transition zone. Differential settlement between the rigid abutment and the backfill under the embankment load leads to the familiar problems of the bump at the bridge head, voids beneath the approach slab, and pavement cracking. Drainage consolidation, replacement filling, lightweight filling, and column reinforcement are all used in practice, but none of them alone can balance shallow deformation compatibility with deep compression control. Shallow in-situ solidification mixes stabilizers into the in-situ soft soil to form an artificial hard crust, which replaces the traditional sand–gravel cushion and works together with deep cement mixing columns; the two form a coordinated system in which the shallow layer regulates deformation while the deep columns suppress compression.

The effectiveness of this system depends largely on the strength and modulus of the solidified soil, which are closely related to the type and content of the stabilizer, the water–cement ratio, the curing age, and the soil properties. On this basis, the present study first determines the mix proportion and the strength and deformation parameters of the solidified soil applicable to the project through laboratory tests, and then investigates the magnitude and mechanism of the influence of the stiffness of the solidified layer on the settlement behind the bridge abutment by means of numerical modelling.

1.2 Literature review

1.2.1 Treatment technologies for the back of bridge abutments

The diseases behind bridge abutments essentially stem from the stiffness contrast between the rigid abutment and the flexible embankment, together with the differential settlement this contrast produces. Three treatment concepts have emerged: stiffening the embankment or the ground to narrow the contrast, inserting transition structures such as approach slabs to smooth the settlement profile, and reducing the additional stress with lightweight fill. Prakash et al.[1] compiled a comprehensive review of bridge-approach settlement — its causes and the available mitigation measures — noting that approach slabs, reinforced embankments, and lightweight backfill each suit different combinations of backfill height and soft-layer compressibility. For embankments on soft clay reinforced by stiffened deep-mixed columns working with rigid piles, Zhang et al.[2] put forward a settlement calculation method and identified the stiffness of the stabilized body and the replacement ratio as the parameters that dominate post-construction settlement. Field measurements and numerical studies reported so far tell a similar story: piled embankments with geogrids, lightweight fill, and approach slabs all reduce differential settlement to some extent, but none of them handles shallow deformation and deep compression at the same time, and their effect becomes limited once the soft layer turns thick.

1.2.2 In-situ solidification and mechanical properties of solidified soil

In-situ solidification uses purpose-built mixing equipment to blend stabilizers forcibly with the in-situ soft soil, creating an artificial hard crust that replaces the traditional sand–gravel cushion and works together with deep mixing columns. Alhamdi and Albusoda[3] reviewed the reinforcement mechanism, design parameters, and field applications of the deep mixing method. Through field and laboratory testing of soft soil improved by soil-cement columns, Rashid et al.[4] found that column strength and the load sharing between columns and soil largely decide how well the improvement works. Kitazume[5] surveyed the latest progress in construction quality control and assurance for the method, and Porbaha[6] gave an early systematic account of the properties of stabilized soil and the

associated design practice. The EuroSoilStab project[7] issued design and construction guidelines for soft organic soils, and Kitazume and Terashi[8] later consolidated the design theory and state of practice of the deep mixing method in a monograph, covering the bearing capacity and consolidation behaviour of improved ground. As for deformation calculation of composite ground, the pile–soil stress ratio and the area replacement ratio remain the key parameters describing how load is shared between piles and soil. The stress correction method, which accounts for stress concentration, is commonly used to obtain an equivalent modulus of the reinforced zone, so that the pile–soil system can be represented by homogeneous material zones instead of modelling piles and soil separately.

1.2.3 Factors influencing the strength and stiffness of solidified soil

How strong and stiff a solidified soil turns out to be depends on how much cementation product is generated and how the soil particles are arranged. Horpibulsuk et al.[9] linked the strength development of cement-stabilized clay to its microstructure and noted that a minimum cement content exists, below which the stabilization effect cannot be ensured. From a large test programme, Consoli et al.[10] found that the strength and stiffness of artificially cemented soils grow with cement content and curing age but fall markedly as water content increases; they suggested characterizing strength by the ratio of porosity to cement content. Lorenzo and Bergado[11] proposed instead the void-ratio/cement-content ratio to describe the fundamental behaviour of cement-admixed clay, while Sasanian and Newson[12] showed that the modulus of cement-treated clay bears a stable relationship to its UCS, which makes it possible to estimate stiffness from a strength test. These findings support calibrating solidified-layer parameters from laboratory tests. Most of them, however, were obtained on remolded soils or with plain cement. Mix design for organic soft soils that allows auxiliary materials to replace part of the cement, and the joint selection of mix proportion, strength, and stiffness, still have to be resolved case by case through testing.

1.3 Research gaps and scope of this study

Existing work has covered bridge-abutment treatments, deep-mixed composite ground, and solidified soil mechanics quite thoroughly, but two gaps remain. Mix proportion studies generally target strength alone: the water–cement ratio — a parameter that reflects both how easily the soil can be mixed and how one soil differs from another — has rarely been quantified in a unified way, leaving little basis for choosing strength and stiffness together. The modulus of the solidified layer is in no better position, since it is usually picked from experience, and few test-calibrated, field-verified studies have shown how much it really matters to abutment settlement. Against this background, and based on a bridge project in East China, the present study first tests the basic properties of the undisturbed soil and the mechanical properties of in-situ solidified soil, in order to fix the recommended mix proportion together with its strength and modulus. A two-dimensional finite element model of the composite ground behind the abutment, with seepage–deformation coupling, is then built to examine how the layer modulus influences settlement. The results are intended to provide a practical basis for the material design and parameter selection of the solidified layer.

2. Project background and treatment scheme

The project is located in the coastal plain on the south wing of the Yangtze River Delta in East China, with a total route length of about 1600 m. The terrain is flat with a dense river network, and the climate is north subtropical monsoon, with an average annual rainfall of about 1156.7 mm; the water content of the shallow soil is easily affected by seasonal rainfall. The project involves three bridges to be reconstructed. After comparison, borehole G19 on the north side of Bridge M was

selected as the sampling point, and representative soil samples were taken at a buried depth of about 2 m after removing the surface overburden.

The site strata can be divided into four categories from top to bottom: a plain fill about 0.9 m thick at the surface; beneath it a ditch fill about 2.0 m thick containing organic matter and humus with poor soil quality; a mucky silty clay about 11.2 m thick interbedded with thin silt layers, in a soft-plastic to flow-plastic state with high compressibility; and relatively hard strata such as sandy silt and silty clay with a total thickness of about 22 m, which can be regarded as the pile-end bearing stratum. The weak layers most directly affected by the load total about 13 m in thickness; the ditch fill is shallowly buried with low strength, and the mucky silty clay is thick, and together they control the post-construction settlement behind the bridge abutment. The natural water content of the shallow soil is easily affected by seasonal rainfall, so drainage and air drying should be emphasized during the construction period. Accordingly, a combined treatment scheme is adopted for the back of the bridge abutment: shallow in-situ solidification forms a hard crust to coordinate the surface deformation, while deep cement mixing columns restrain the deep compression.

3. Laboratory tests on mechanical properties of solidified soil

3.1 Test program

The mechanical property tests of the solidified soil were performed in accordance with the relevant standards. The specimens for the unconfined compressive strength (UCS) test were cylinders of $\phi 50$ mm $\times$ 50 mm, tested after standard curing to ages of 3, 7, 14, and 28 d, with six parallel specimens for each group. The compressive resilient modulus test used cylindrical specimens of $\phi 100$ mm $\times$ 100 mm, and the value at 90 d was taken as the evaluation basis; the cement used in the tests was the same as that used at the construction site. The basic indices of the undisturbed soil were determined according to the geotechnical test standards. Because the ditch fill contains organic matter, the water content test was carried out by oven drying at a constant temperature of 70 °C. The measured natural water content was 31.60%, the liquid limit was 38.8%, the plastic limit was 22.9%, the optimum water content was 19.89%, and the maximum dry density was 2.08 g/cm³; providing basic parameters for the mix design and the compaction control of construction.

3.2 Water–cement ratio index test

The traditional water–cement ratio does not account for soil differences, leading to large errors in predicting the strength of cemented soils of different soil types. To this end, the water–cement ratio index, defined as the ratio of the water–cement ratio to the liquid limit, is introduced to reflect the differences in soil type. With the cement content fixed at 8% of the wet soil mass, specimens were prepared at water–cement ratios of 1.0, 1.5, and 2.0 and cured for 7 d; the results are listed in Table 1.

Table 1 UCS and water–cement ratio index under different water–cement ratios

Water–cement ratio	1.0	1.5	2.0
Water–cement ratio index	4.544	5.833	7.122
UCS / kPa	836	627	564

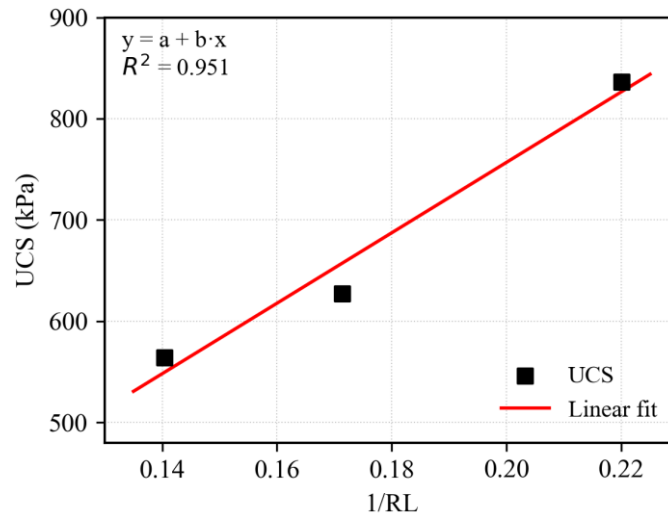


Figure 1 Relationship between UCS and the water–cement ratio index

A linear fit between the reciprocal of the water–cement ratio index and the UCS gives a correlation coefficient $R^2 = 0.951$ (Fig. 1), indicating a good linear relationship: the smaller the water–cement ratio index, the less unreacted free water remains in the soil, the weaker the lubrication of the soil particles, and the higher the strength of the solidified soil. Although a higher strength is obtained at a water–cement ratio of 1.0, the slurry is viscous at this ratio with large mixing resistance, making uniform mixing difficult to guarantee with field equipment. Considering the mixing difficulty, the strength level, and the engineering feasibility, a water–cement ratio of 1.5 is recommended.

3.3 Unconfined compressive strength tests

Four cement content levels of 4%, 6%, 8%, and 10% were set, and the UCS at each curing age was measured; the 28 d strengths are listed in Table 2.

Table 2 Influence of cement content of the single stabilizer on UCS

Group	3 d strength / kPa	7 d strength / kPa	14 d strength / kPa	28 d strength / kPa
10% cement	603	687	923	1095
8% cement	471	612	769	913
6% cement	416	481	568	685
4% cement	243	316	368	439

The strength increases gradually with the cement content and the curing age, but the growth rate slows down with time. Taking the 8% cement group as an example, the 3 d strength is about 500 kPa, and the 14 d strength reaches about 80% of the 28 d strength (Fig. 2). For every 2% increase in the cement content, the 28 d strength increases by about 200 kPa, but the increment tends to level off when the cement content exceeds 8%.

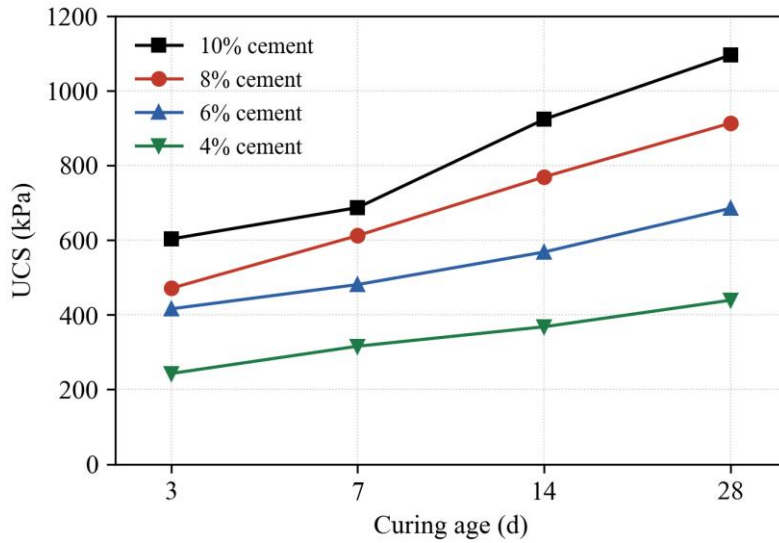


Figure 2 Strength development of solidified soil with curing age under different cement contents

With the cement content fixed at 8% and the curing age at 7 d, four water content levels of 29%, 31%, 33%, and 35% were set; the results are shown in Fig. 3.

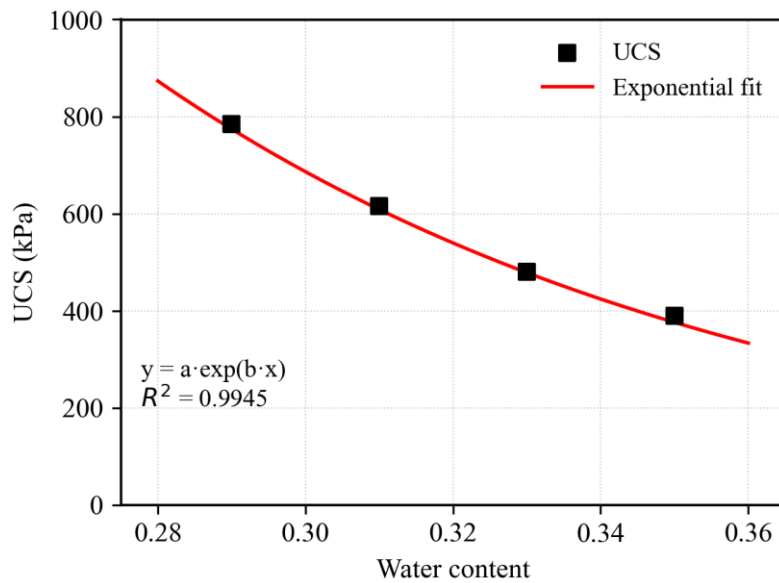


Figure 3 Effect of water content on the UCS of solidified soil

With increasing water content, the UCS of the solidified soil decreases exponentially, with a fitting correlation index of 99.45%: when the water content increases from 29% to 33%, the strength decreases by about 23%. This is attributed to the fact that a higher water content reduces the amount of hydration products per unit volume and weakens the cementation. The water content of the undisturbed soil should therefore be emphasized in construction, and measures such as drainage, air drying, or adjusting the stabilizer content should be taken when necessary.

Keeping the total stabilizer content at 8% of the wet soil mass, part of the cement was replaced by activated mineral powder, gypsum, and a soil-stabilizing additive, respectively; the 28 d UCS values are listed in Table 3 and shown in Fig. 4. Active mineral powder has both filling and pozzolanic

effects, and the strength changes little when the replacement does not exceed 2%; the strength of the gypsum group decreases with increasing replacement; the additive group shows little difference from the control group and exhibits no stable trend with the additive content, so it is not included in the recommended scheme.

Table 3 28 d UCS of different solidification schemes

Specimen group	28 d UCS / kPa
8% cement (control)	913
6% cement + 2% activated mineral powder	817
6% cement + 2% gypsum	807
8% cement + 0.05‰ additive	909

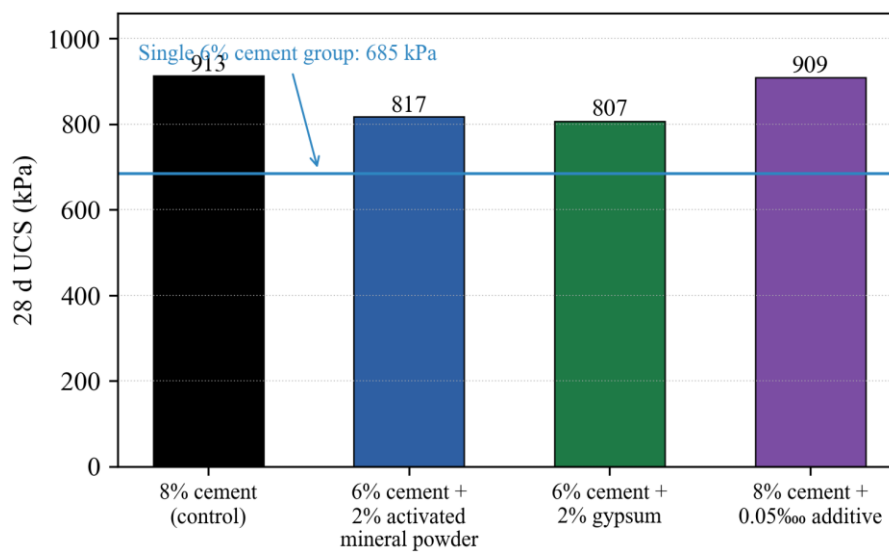


Figure 4 Comparison of 28 d UCS of different solidification schemes

A comprehensive comparison shows that the 28 d UCS of 6% cement + 2% activated mineral powder is 817 kPa, about 19.3% higher than that of the single 6% cement group (685 kPa), and that of 6% cement + 2% gypsum is 807 kPa, about 17.8% higher, with similar improvement effects. Considering the strength, the material source, and the construction workability, the composite scheme of 6% cement + 2% activated mineral powder is recommended.

3.4 Compressive resilient modulus test

The compressive resilient modulus at 90 d was measured by the stepwise loading–unloading method. The results show that, for the cement-only groups, the resilient modulus increases with the cement content, from about 45 MPa for the 4% cement group to about 66 MPa for the 10% cement group; under the total stabilizer content of 8%, the resilient moduli of the composite groups with various replacement ratios of activated mineral powder are all between 57 and 59 MPa, comparable to that of the 8% cement control group. This indicates that an appropriate amount of activated mineral powder replacing cement can increase the strength while keeping the deformation modulus from decreasing.

3.5 Determination of mix proportion and model parameters

The above tests provide material indices of the solidified soil, which still need to be converted into model parameters of the solidified layer for numerical computation. As a shallow hard crust, the solidified layer fails mainly in compression and shear, so the 28 d UCS is taken as the strength control index. According to the parameter conversion relations of the linear Drucker–Prager model, the hardening parameter is determined from the uniaxial compressive yield stress, and the test strength is converted into the inclination angle and the intercept of the yield surface by combining the cohesion and the internal friction angle. The deformation behaviour is determined by the 90 d compressive resilient modulus, which is 58 MPa for the recommended mix proportion. The geometry and density of the solidified layer are also matched with the test results and the equipment conditions: the thickness is 3 m, the density is taken as 1900 kg/m³ converted from the maximum dry density and the mix proportion, and the cement content is 6% of the wet soil mass. When the mix proportion or the curing age changes, the modulus can be adjusted synchronously according to its stable correspondence with the UCS. Table 4 is thereby taken as the input condition of the numerical model.

Table 4 Parameters of the solidified layer for numerical modelling

Parameter category	Value	Source and basis
Mix proportion	6% cement + 2% activated mineral powder, water–cement ratio 1.5	Comparison of water–cement ratio and composite schemes
Compressive strength	817 kPa	28 d UCS test value
Deformation modulus	58 MPa	90 d compressive resilient modulus test value
Dry density	1900 kg/m ³	Converted from maximum dry density and mix proportion
Cement content	6% (wet soil mass)	Recommended composite solidification scheme

4. Numerical analysis of the modulus effect of the solidified layer

4.1 Computational model

To convert the test results into computable conditions for the settlement behind the bridge abutment, the two-dimensional finite element method is adopted, considering the coupling of seepage and deformation. The computation follows an elastic layered system: the three-dimensional problem is simplified to a plane strain problem, the soil of the same layer is regarded as homogeneous and isotropic, the filling load is applied in stages according to the construction sequence, displacement continuity is maintained between the interfaces, and the short-term disturbance of the underlying soft soil caused by the solidification construction is not considered. The solidified layer is arranged close to the abutment back wall, with a thickness of 3 m and a longitudinal length of 10 m along the road. The deep mixing column zone is not modelled with explicit columns; instead, it is converted into homogeneous composite material zones according to the area replacement ratio and the pile–soil stress ratio. The layered filling of the embankment is simulated by “killing and reactivating” elements: the backfill elements in the not-yet-filled area are “killed” in the initial geostress balance step and reactivated layer by layer as the analysis steps proceed, reproducing the gradual application of the load.

4.2 Parameter calibration and model validation

The key to the model computation lies in whether the material parameters can be directly calibrated from the tests. The natural ground soil and the fill are valued according to the survey data and conventional geotechnical tests, with the Drucker–Prager elastoplastic model as the constitutive relation; the abutment, the approach slab, and the pavement structural layers are treated as linear elastic materials; and the parameters of the solidified layer are entirely taken from Section 3.5 (Table 4), without assuming its modulus and strength empirically.

To verify the rationality of the above parameter calibration, the computed settlement is compared with the field monitoring results. The computed settlements of the solidified and non-solidified sections differ from the measured averages by 0.24 mm and 0.14 mm, respectively, both less than 0.3 mm, and their variation trends are consistent with the measured process, indicating that the solidified layer parameters determined from the tests can reflect the actual working state and that the model can be used for the subsequent parameter analysis.

4.3 Effect of the elastic modulus of the solidified layer on settlement

The elastic modulus and thickness of the solidified layer are design parameters that can be directly calibrated; the modulus is determined by the mix proportion and the curing age of the solidified soil. To examine the influence of the modulus on the settlement behind the bridge abutment, only the elastic modulus of the solidified layer was varied in the computation, with five cases of 60, 80, 100, 120, and 140 MPa and all other conditions kept unchanged. The measured 90 d compressive resilient modulus corresponding to the recommended mix proportion is 58 MPa, near the lower bound of the above range, which provides a test basis for the low-modulus case. The computed settlements of the solidified and non-solidified zones for each case are shown in Fig. 5.

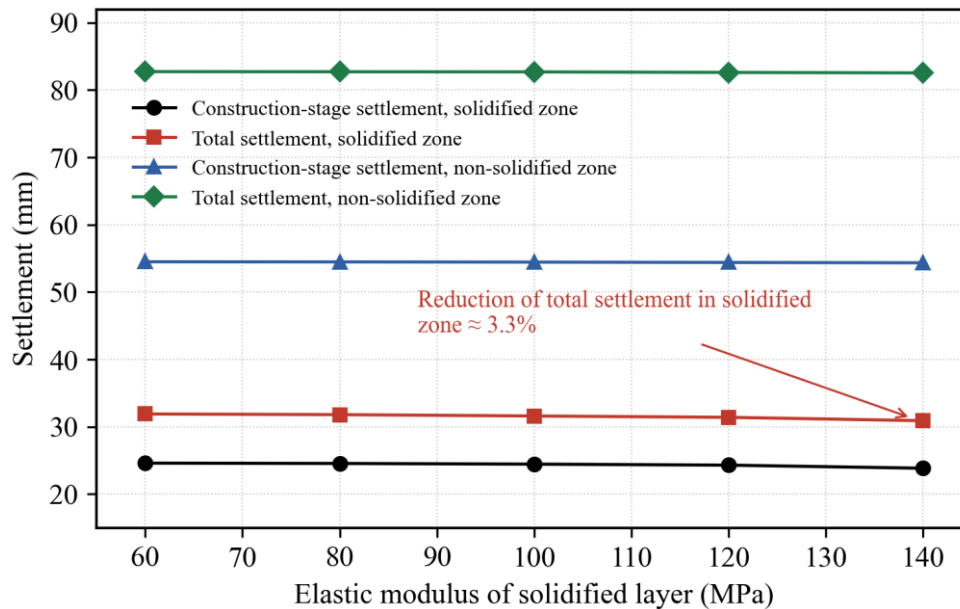


Figure 5 Effect of the elastic modulus of the solidified layer on the ground settlement behind the bridge abutment

As shown in Fig. 5, when the modulus increases from 60 MPa to 140 MPa, the construction-stage settlement and the total settlement of the solidified zone decrease from 24.60 mm and 31.90 mm to 23.84 mm and 30.90 mm, respectively, a reduction of about 3.3%; the total settlement of the non-

solidified zone decreases slightly from 82.74 mm to 82.55 mm, by less than 1%. The settlement curves are nearly horizontal over the modulus range, indicating that the settlement behind the bridge abutment is insensitive to the stiffness change of the solidified layer. The mechanism is as follows: the settlement of the system is mainly controlled by the underlying mucky soft layer, whose modulus is only 10–25 MPa and whose compressibility is high; although a higher stiffness of the solidified layer reduces the compression of the surface layer itself, it also transfers more additional stress downward, and the deep soil continues to produce plastic compression under the higher effective stress, so that the stiffness gain of the surface layer is partly offset.

This result has direct implications for the design: increasing the modulus of the solidified soil from about 58 MPa to 140 MPa requires a significant increase in the cement consumption or denser mixing, whereas the improvement in the total settlement is only about 1 mm, so the cost-effectiveness of trading a higher modulus for settlement control is low. The mix proportion of the solidified layer should therefore be determined on the principle of satisfying the strength, the durability, and the construction workability, corresponding to the modulus level of the recommended mix proportion; the settlement control should rely more on the coordinated adjustment of the thickness of the solidified layer and the column parameters (column diameter and spacing). It should be noted that the analysis in this paper is based on a two-dimensional plane strain model and specific stratigraphic conditions; when the soft layer is thin or the solidified layer is thick, the influence of the modulus may become more significant and needs to be further verified in combination with specific projects.

4.4 Comparative analysis of modulus and thickness

The thickness of the solidified layer determines the depth range of load diffusion and reinforcement, and together with the modulus constitutes the two designable parameters of the solidified layer. To compare their effects on the same scale, thicknesses of 1.5, 2.0, 2.5, 3.0, and 3.5 m were computed; the results are shown in Fig. 6. When the thickness increases from 1.5 m to 3.5 m, the total settlement of the solidified zone decreases from 33.99 mm to 30.62 mm, and that of the non-solidified zone decreases from 83.34 mm to 82.54 mm; that is, for each additional 1 m of thickness, the total settlement of the solidified zone decreases by about 1.68 mm on average. By comparison, when the modulus increases from 60 MPa to 140 MPa, the total settlement of the solidified zone decreases by only about 1.00 mm; more than doubling the modulus yields less than half of the settlement improvement obtained by adding 1 m of thickness.

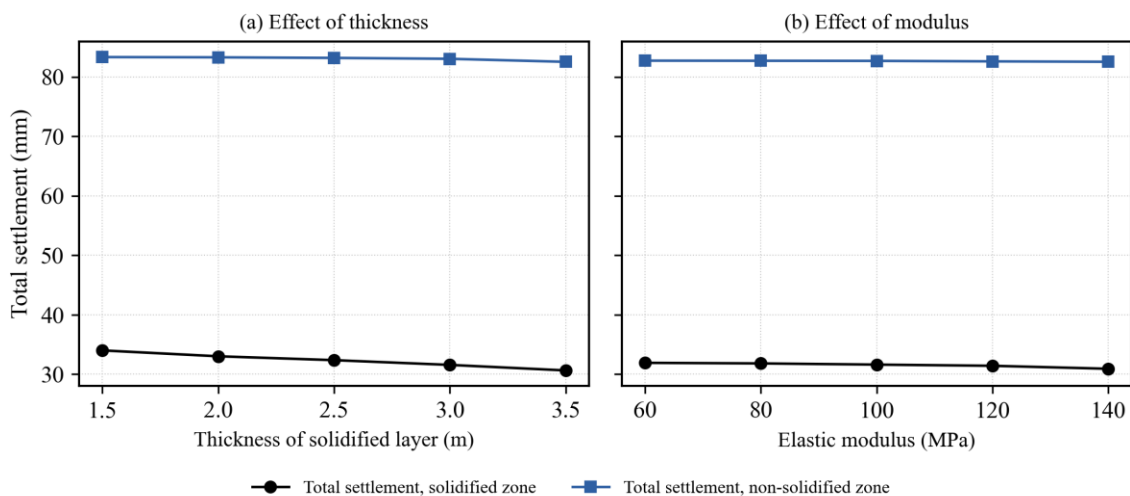


Figure 6 Comparison of the effects of thickness and elastic modulus on the total settlement

Combining the results of the two parameters, the contour map of the total settlement of the solidified zone versus the modulus and the thickness can be drawn (Fig. 7). The contour lines are generally steep straight lines, and the settlement gradient in the thickness direction is obviously greater than that in the modulus direction. Within the ranges of 60–140 MPa for the modulus and 1.5–3.5 m for the thickness, the total settlement of the solidified zone lies between about 29 and 34 mm. The test modulus (58 MPa) lies at the left end of the range, indicating that the stiffness of the solidified layer constructed with the recommended mix proportion has already entered the gentle segment of the settlement curve.

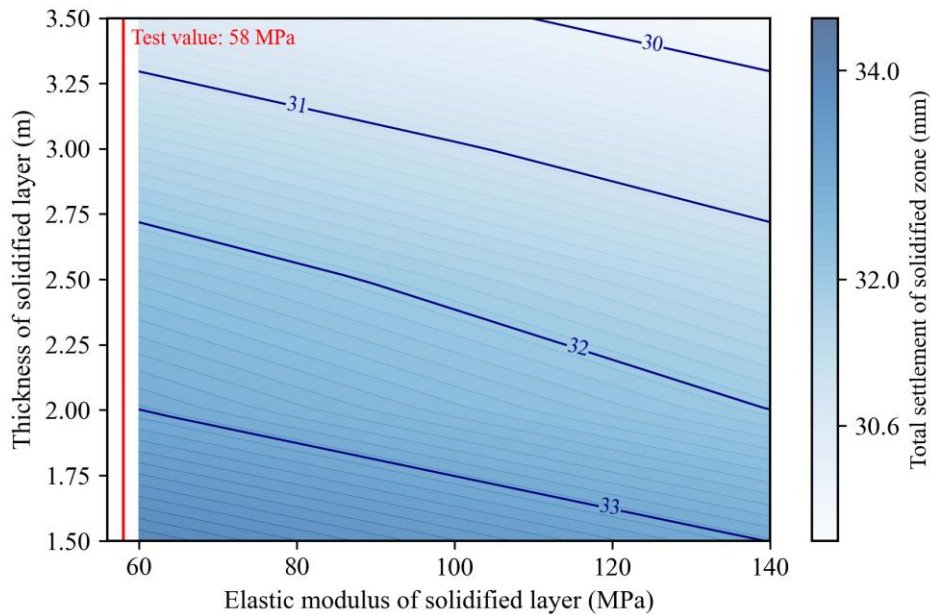


Figure 7 Contour map of the total settlement of the solidified zone versus the modulus and the thickness

4.5 Settlement control efficiency and recommended parameter values

In engineering practice, what matters is “at what cost and for how much settlement control effect”. For this purpose, a settlement control efficiency index is introduced, defined as the reduction of the total settlement of the solidified zone per unit cement consumption, with the recommended mix proportion case as the benchmark. For the modulus: referring to the laboratory test relation in which the 90 d resilient modulus increases from about 52 MPa to about 66 MPa when the cement content increases from 6% to 10%, raising the modulus from 58 MPa to 140 MPa would require an additional cement consumption of about 160 kg/m^3 ; while the total settlement of the solidified zone decreases by only about 1.0 mm, a reduction of about 3%. For the thickness: each additional 1 m of thickness increases the cement consumption per unit area of the solidified soil by about 114 kg/m^2 ; and the total settlement of the solidified zone decreases by about 1.68 mm, a reduction of about 5%. In comparison, the settlement control efficiency of thickening is about 5–6 times that of increasing the modulus. Therefore, within the capacity of the equipment (generally no more than 5 m), thickening should be prioritized to improve the settlement, and the modulus should be kept at the level corresponding to the recommended mix proportion; the remaining settlement should be resolved by adjusting the column parameters such as the column diameter and the spacing, avoiding blindly increasing the cement consumption in pursuit of a high modulus.

5. Economic discussion

The cost of the combined treatment system is mainly determined by the material input, of which cement is the main cost source shared by the solidified layer and the mixing columns; therefore, the mix proportion and thickness of the solidified layer and the column parameters are the direct factors affecting the engineering economy. With the composite mix proportion of 6% cement + 2% activated mineral powder, replacing part of the cement with activated mineral powder not only increases the strength of the solidified soil and maintains the resilient modulus, but also reduces the unit price of the cementitious materials and consumes industrial by-products. In-situ solidification eliminates the material input of the sand–gravel cushion as well as the procedures of excavation, replacement, and spoil transportation, reducing the earthwork transportation and disposal costs and shortening the foundation treatment period. Combined with the efficiency analysis in Section 4.5, the settlement benefit of increasing the modulus is limited while the cost increase is obvious; moderately increasing the thickness within the capacity of the equipment, and back-calculating a reasonable replacement ratio of the columns from the settlement control standard, is an effective way to balance the settlement control and the cost.

6. Conclusions

Based on a bridge project in East China, this study takes the laboratory tests on the mechanical properties of in-situ solidified soil as the core, calibrates the parameters of the solidified layer, and analyses its modulus effect through numerical modelling. The main conclusions are as follows:

1) The water–cement ratio index — the water–cement ratio divided by the liquid limit — works well for removing soil-type effects from the picture: the UCS of solidified soil rises almost linearly with the reciprocal of this index ($R^2 = 0.951$). Strength is not the only consideration at the mixing stage. At a water–cement ratio of 1.0 the slurry becomes too viscous for the field equipment to mix uniformly, so 1.5 is recommended as the compromise.

2) Strength responds most directly to cement content and curing age, and it develops quickly at early ages — the 14 d strength already reaches about 80% of the 28 d value. Water content, by contrast, is the factor that governs whether the stabilization works at all: the strength decays exponentially as water content increases (fitting index 99.45%), so the in-situ moisture condition deserves close attention during construction.

3) Among the composite schemes tested at a total stabilizer content of 8%, 6% cement + 2% activated mineral powder performs best. Its 28 d UCS of 817 kPa exceeds that of the single 6% cement group by about 19.3%, while its 90 d resilient modulus stays at 57–59 MPa, on a par with the 8% cement control. Strength therefore improves without sacrificing stiffness, and this scheme is put forward as the engineering mix proportion.

4) Feeding the measured strength, modulus, density, and thickness directly into the numerical model gives settlements that differ from the field measurements by only 0.24 mm in the solidified zone and 0.14 mm in the non-solidified zone. The agreement is close enough to confirm that test-calibrated parameters represent the real working state of the layer, closing the loop between laboratory testing and numerical analysis.

5) Varying the elastic modulus of the solidified layer from 60 MPa to 140 MPa changes the total settlement of the solidified zone by only about 3.3%, and that of the non-solidified zone by less than 1% — settlement is only weakly sensitive to the modulus. The reason is that the extra stiffness sheds more load onto the highly compressible soft clay beneath, so part of the compression saved in the surface layer reappears in the deep layer. Chasing a high modulus is therefore not worthwhile; the modulus should simply be kept at the level that guarantees strength, durability, and workability.

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