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Research Article

Cause Analysis and Countermeasures of Through Shakes in Foamed Concrete Subgrade

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The paper presents a new type of material—foamed concrete—adopted for expansion subgrade of the expressway. Intriguingly, the irregular through shakes appear on its top. The method combining the engineering case, theoretical analysis, and numerical simulation is employed to analyze its T-shaped and tree-shaped through shake. The research indicates that when the underground water table is high, cracks are easily seen on the top of step-shape foamed concrete due to buoyancy force. Under the concentrated load effect, the maximum displacement of 27.09 mm is observed on the top of the simply supported beam when elastic modulus is 200 MPa. The maximum principle tensile stress of 0.34 MPa also occurs on the top of the simply supported beam when elastic modulus is 200 MPa and 400 MPa, which is greater than tensile strength of foamed concrete of 0.31 MPa and 0.26 MPa at 7 d and 28 d, respectively. Thus, the adoption of a simply supported beam structure fits site through crack. To avert cracks on the top of foamed concrete in high groundwater table, the antibuoyancy measures should be adopted prior to construction of the upper bearing stratum. The study has expanded the application scope of subgrade and enriched theory of foamed concrete filled in high groundwater table, providing a significant reference to similar projects.

1. Introduction

As a new type of material, foamed concrete was used in Japan and America in the 1980s and was later introduced to China in 2001. In recent years, it has gained more attention and is widely applied in our country [1, 2]. Foamed concrete, a composite material produced by adding liquid foam in cement paste, features light mass (density is approximately 0.5, half density of water), low strength (low up to 0.8–2 MPa), and high porosity (over 50 percent). The preliminary use demonstrates that foamed concrete has significant advantages that other ordinary subgrades may not possess, such as rapid construction speed, low cost, good compactness, ability to fill the gap in blocky materials during pouring, ability to satisfy the strength requirement of ordinary subgrade after cement setting and hardening, ability to gratify back strength and compactness requirement of ordinary bridge back, ability to greatly reduce effective dead weight, ability to lower foundation stress, reduce foundation differential settlement, and absorb impact energy of the upper-stratum road, and ability to overcome car jumping when passing backfill of bridge back subgrade caused by ordinary filling. Since the Lecheng expressway is open to traffic, the traffic volume remains high, causing tremendous traffic pressure, among which the traffic volume of the road extending from Qinglong Chang (K43 + 000) to Meishan (K71 + 000) is observed to be 37153 pcu/d since 2015, attaining 70 percent of the design traffic volume. With the in-depth implementation of the construction of Tianfu New District, the transportation demand of this section is bound to be more vigorous. The road at this section is being expanded. After the expansion project is completed, it will effectively ease the traffic pressure and optimize the road network layout [3].

The right subgrade of the test section K59 + 458~K59 + 580 for the expansion project of the Chengle expressway from Qinglong Chang to Meishan (hereinafter referred to as the project) is filled using foamed concrete (Figure 1). The section belongs to the flat landform characterized by a flat terrain and surface layer of different thicknesses ranging from approximately 12 m to 23 m, which is covered by artificial fill, silty clay, fine sand, and pebble. Under the surface layer, there is silty mudstone strongly and moderately weathered. It is developed in the unfavorable geology and partially grown in the weak soil.

During construction, it is observed that through shakes of different levels appear at the top of foamed concrete to the right of Section II of K59 + 520~K59 + 540. The layer is 0.6 m away from the top of design foamed concrete subgrade.

Experts at home and abroad have conducted many studies by combining laboratory tests and engineering applications, achieving fruitful results. She et al. [4] indicated that foamed concrete, serving as subgrade filling of the expressway, boasts favorable loading capacity and sedimentation reduction. Tan et al. [5] indicated that cracks are easily observed on high-density foamed concrete under high temperature and that pore connectivity and surface peeling are easily seen on low-density foamed concrete. Daneti et al. [6] indicated that the polypropylene fiber can enhance flexural toughness of foamed concrete and is able to control shrinkage cracks of foamed concrete. By conducting immersion, water absorption, and floating resistance tests to the sample of foamed concrete, Wang et al. [7] studied the change rule of structure works subject to buoyancy under immersion and floating resistance as well as water-absorbing capacity of foamed concrete when being served as a filler. Emiko et al. [8] studied shearing transfer between lightweight aggregate concrete and foamed concrete. Cheng [9] indicated that the compressive strength and separation tensile strength of foamed concrete demonstrate linear correlation with preliminary wet density. Amran et al. [10] studied foam size distribution of foamed concrete and pore size distribution after foamed concrete is hardened. Caduff and van Mier [11] studied the crack on ordinary concrete, high-strength concrete, and foamed concrete under uniaxial compression. The evaluation method of the asphalt pavement in Slovak Republic is introduced, and the favorable prospect of foamed concrete applied in road construction is also indicated [12, 13]. Deng [14] studied the relation between immersion and lightweight concrete density and summarized deformation and fracture characteristics and stress-strain law. Huang et al. [15] analyzed the static and dynamic intensity of foamed concrete through compressive strength and dynamic triaxial tests, showing that the strength of foamed concrete can satisfy static and dynamic conditions of nonballast track subgrade and the requirement of foamed concrete filled in nonballast track subgrade. Bayuaji and Nuruddin [16] studied the influence of microwave incinerated rice husk ash (MIRHA) powder on foamed concrete (FC) hydration.

However, there are few studies in regard to foamed concrete subgrade filled in underground water, particularly section of the inverted step that is small at the bottom and big at the top. And there are no reports regarding foamed concrete subgrade designed and implemented in high underground water table nor relevant countermeasure and study on its crack. The paper intends to analyze the cause of crack at the top of foamed concrete and proposes the applicable condition of foamed concrete subgrade through two key factors such as inverted step and underground water, offering important references for design and construction of other similar projects.

Figure 1: K59 + 520~K59 + 540 right lightweight foamed concrete subgrade.

2. Example of Through Shake in Foamed Concrete Subgrade

The design requires that compressive strength of foamed concrete at this section be no less than 1.0 MPa. The foamed concrete is made using normal Portland cement P.O42.5, water, and high-performance foaming agent (liquid foam) per certain proportion. The design mix proportion of foamed concrete in the paper refers to standard CECS/249: 2008 [17]. First, the trial mix strength of foamed concrete is determined per formula (1). Second, the design wet density and each component of foamed concrete are determined per formulas (2) and (3). A combination of engineering experience is also required as necessary; the fine aggregate sand is not adopted in the project. Finally, the wet density, flow value, and compressive strength tests are performed according to the calculated mix proportion, showing that each index satisfies the final mix proportion as required by the design and standard requirement (Table 1):

$$q_u \geq 1.05 q_c, \tag{1}$$

where q_u is the trial compression strength of foamed concrete (MPa) and q_c is the designed compression strength of foamed concrete (MPa):

$$\rho_w = R_c + R_s + R_w + R_f + R_x, \tag{2}$$

$$R_f = \rho_f \cdot \left(1 - \frac{R_c}{\rho_c} - \frac{R_s}{\rho_s} - \frac{R_w}{1000} - \frac{R_x}{\rho_x}\right), \tag{3}$$

Table 1: Trial mix proportion and testing result of foamed concrete.

Water-binder ratio	Unit volume (kg/m^3)				Dilution ratio	Mass ratio	
	Cement	Water	Foaming agent	Admixture		Water	Foaming agent
0.65	325	211	13	—	25	1	0.04

where R_c is the mass of cement per cubic meter in foamed concrete (kg/m^3), R_s is the mass of aggregate per cubic meter in foamed concrete (kg/m^3), R_w is the mass of water per cubic meter in foamed concrete (kg/m^3), R_f is the mass of foam per cubic meter in foamed concrete (kg/m^3), R_x is the mass of admixture per cubic meter in foamed concrete (kg/m^3), ρ_w is the design wet density of foamed concrete (kg/m^3), ρ_c is the cement density (kg/m^3), ρ_s is the aggregate density (kg/m^3), ρ_x is the admixture density (kg/m^3), and ρ_f is the density of standard foam (kg/m^3).

The main raw material used in the mix proportion includes cement and foaming agent, where the cement is the ordinary Portland cement P.O42.5 manufactured by Sichuan Esheng Group and the foaming agent is the XL-type polymeric foaming agent manufactured by Guangzhou Xianglu Municipal Works Company. Table 2 shows the testing index of the foaming agent.

It is demonstrated through the mix proportion test, verification, and site sampling that compressive strength fluctuates from 1.2 MPa to 2.0 MPa, with the average compressive strength of 1.6 MPa and the standard deviation of compressive strength of 0.163 MPa; wet density fluctuates from 540 kg/m^3~580 kg/m^3, with the average wet density of 560 kg/m^3; and flow value ranges from 160 mm to 180 mm. The design requires that every 10 m along the length direction should be fitted with a settlement joint. In the course of construction, cracks are seen in two foamed concrete subgrades at K59 + 520~K59 + 530 and K59 + 530~K59 + 540 and through shakes appear. The top of lightweight foam subgrade at these two sections has not reached up to its top. It is 0.6 m away from the design top; namely, through shakes are shown on the top of foamed concrete before concrete filling is completed. The pouring of the upper layer can be carried out at 1 d~2 d after the bottom layer is poured.

2.1. T-Shaped Through Shakes Appearing at K59 + 520~K59 + 530. T-shaped through shakes are observed at K59 + 520~K59 + 530, as shown in Figures 2–4, among which the first shake covers through horizontal road width with length exceeding 830 cm that looks like a large radius arc. The shake has a depth of approximately 260 mm and a width of approximately 0.6 mm. The second shake, virtually perpendicular to the first shake that shows an approximate straight line, features a length of 380 cm and a shake depth and width of 150 mm and 0.4 mm, respectively. The first shake is way greater than the second shake in terms of length, width, and depth.

The design and site pit excavation disclose that the section at this area shows significant inverted step shape (positive T-shape), consisting of two steps. The width and height of the bottom step are 342 cm and 100 cm, respectively. The width and height of the top step are 830 cm and 112 cm, respectively. The left and right steps are roughly distributed.

Table 2: Test of foaming agent performance.

Name No.	High-performance foaming agent Item	Unit	Standard	Result
1	Foam expansion	Times	—	40
2	Bubble sedimentation	mm	<5	4
3	Bubble water immersion	ml	<25	16

2.2. K59 + 530~K59 + 540 Primary and Secondary Tree-Shaped Through Shakes. Primary and secondary through shakes at K59 + 530~K59 + 540 are shown in Figures 5–7. The through shake appears like a tree trunk and branch by means of overall horizontal monitoring. The main crack extends vertically from Chengdu to Leshan, exceeding half of the settlement joint length. The length is approximately 680 cm that looks like a tree trunk with crack depth 290 mm and crack width approximately 0.4 mm. The secondary crack lies in the upper branch of primary cracks, which seems like a tree branch with different lengths. The length of the secondary crack is smaller than that of the primary crack. The crack width is approximately 0.3 mm.

The design and site pit excavation disclose that the section at this area shows inverted step shape, which encompasses four steps. The width and height of the lower step are 303 cm and 100 cm, respectively. The width and height of the upper step are unevenly distributed, and the left and right sides are asymmetrically distributed.

3. Theoretical Analysis of Through Shakes on Foamed Concrete

Generally, the structural crack falls into two categories—through shake and cut-through microcrack. The through crack is certainly caused by the structure that suffers from internal and external force. The through crack may exert substantial effect on internal structure stress. Caused by surface temperature shrinkage due to delayed maintenance, the microcrack has limited effect on structure stress. The exclusive method is adopted to analyze through shake on foamed concrete at the right side of the road section K59 + 520~K59 + 530 and K59 + 530~K59 + 540, eliminating internal force effect such as hydration heat. And attention is more switched to external force. In seeking external force, painstaking efforts have been made and many opinions appear and controversy persists, so there is no convincing explanation. The external force consists of horizontal force and vertical force. The traffic operates normally at the left side of the Chengle expressway. The subgrade tends to be stable, and natural soil at the right side is stable. This can

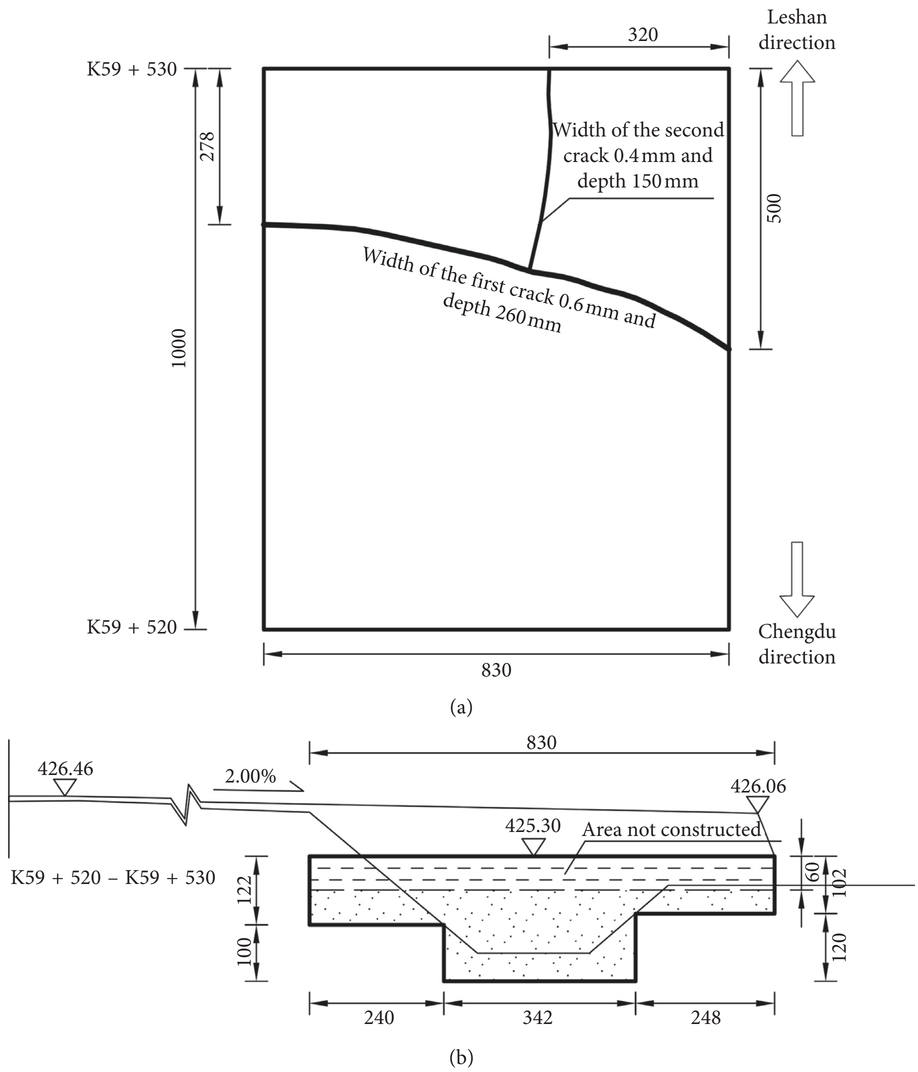


Figure 2: Plane graph (a) and section schematic diagram (b) of K59 + 520~530T through shakes. Dimensions: elevation in m; distance in cm; crack width in mm; depth in mm.

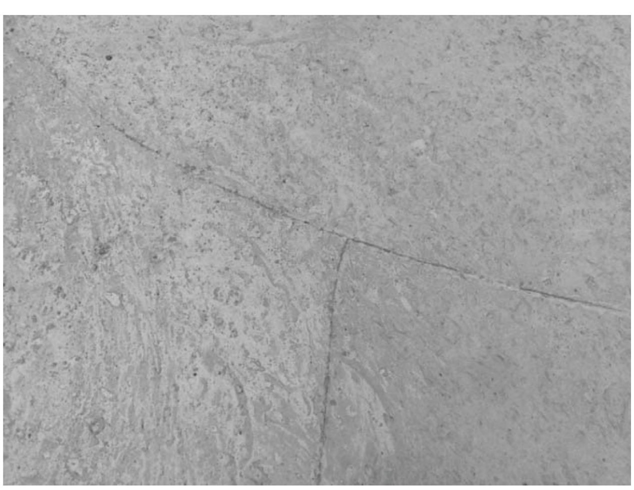


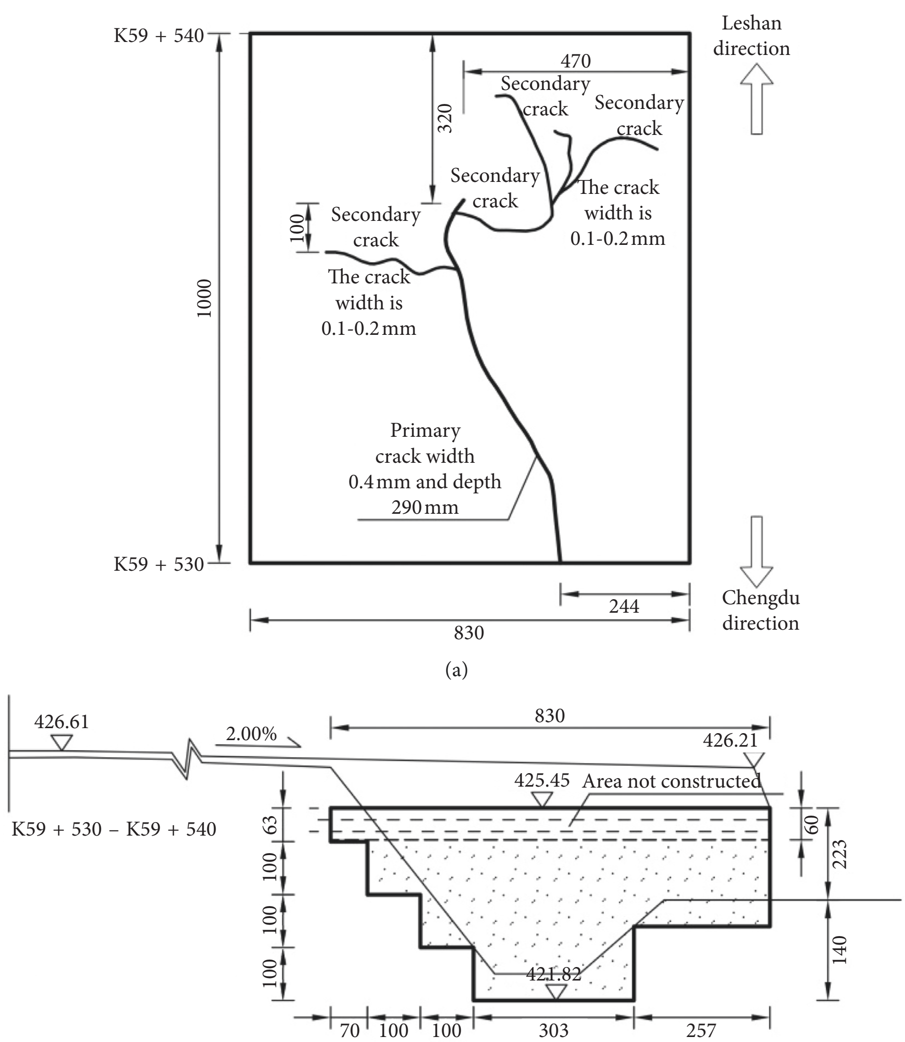
Figure 3: Macrophotograph of K59 + 520~K59 + 530 T-shaped through shakes.

eliminate the effect of horizontal external force, leaving vertical external force considered.

The vertical external force includes external force of foamed concrete from top to bottom and external force from bottom to top. During the construction period, there are no vehicles driving on the road and traffic operates only on temporary access road at the right side. In other words, even temporary vehicle has not passed through the top of foamed concrete; thus, there should be no possibility of external force from top to bottom. In this case, there is only external force coming from bottom to top of foamed concrete. Some holds the opinion that the crack is caused by external force generated from base soil of foamed concrete. The stratum at this area is well distributed and stable, so the opinion is quickly denied. Some believe crack may be caused by water seepage pressure that drives foamed concrete bulge. Figure 1 shows that surface water is close to the top of foamed concrete. The landform at this area is flat and base is sand

(a) (b)

Figure 4: Test pit image of K59 + 520~K59 + 530 T-shaped through shakes.



(b)

Figure 5: Plane graph (a) and section schematic diagram (b) of primary and secondary through shakes at K59 + 530~K59 + 540. Dimensions: elevation in m; distance in cm; crack width in mm; depth in mm.

gravel of good water permeability. The height of foamed concrete is merely 200 cm, which does not make sense if crack is only attributed to groundwater penetration pressure. This may lead to crack but is not the major factor causing through shake as per actual situation of the layer of water permeability.

Figure 6: Image of K59 + 530~K59 + 540 primary and secondary through shakes.

Figure 7: Pit picture of primary and secondary through shakes.

The team sorted out an important cause after long-term analysis. The lower step is fully soaked in water and is subject to upper buoyancy. The foamed concrete of the surface layer on the upper step is above water, which is free from buoyance (Figure 1). The upward buoyance causes tension to the surface of foamed concrete, and the tensile strength of foamed concrete is extremely low, leading to through shake on its surface.

Taking K59 + 520~K59 + 530 as an example, the explanation is given as follows (Figure 2). The foamed concrete in Figure 2 is divided into three pieces—piece ①, piece ②, and piece ③, among which piece ② is split into ②-1 piece and ②-2 piece. To simplify calculation, piece ① and piece ③ are regarded to have equal height, and the average value of piece height 112 cm is set as piece height. Taking the average width of piece ① and piece ③ 244 cm as their width and placing piece ② in the middle of piece ① and piece ③, a symmetrical piece is formed (Figure 8(a)). The stress in Figure 8(a) is simplified by taking pieces ①, ②-1, and ③ as the beam structure layer and regarding upward buoyance of piece ②-2 as the well-distributed load; meanwhile, concentrated force F is used to replace the well-distributed load, offering a new diagram that fits actual structure stress, namely, a simply supported beam that bears concentrated load in the span (Figure 8(b)). The simply supported beam has a length of 830 cm, a height of 50 cm, and a width of 100 cm (every linear meter). The material constituted is foamed concrete. The unit weight adopts the actual wet density 560 kg/m^3.

Given that piece ②-2 is fully soaked into water and other pieces are above water which is not affected by buoyance, the piece ②-2 buoyance is calculated as per formula (4) and Archimedean principle:

$$F = \rho g V. \tag{4}$$

The buoyance of piece ②-2 is obtained as $F = 34200$ N (Table 3).

The buoyance that piece ②-1 suffers is provided by piece ②-2, which is 34200 N; namely, the buoyance of whole piece ② is 34200 N.

The upward force that piece ②-1 suffers is equal to buoyance minus self-weight of piece ②. Per calculation (5), upward force is equal to upward force of the unit area, which is indicated using formula (6):

$$F_{\mathrm{A}} = F - G, \tag{5}$$

$$f = \frac{F - G}{A}. \tag{6}$$

The gravity of piece ② is the total gravity G of piece ②-1 and piece ②-2: $G = 19152 + 9576 = 28728$ N.

Therefore, the upward force that piece ②-1 suffers is calculated as $F_{\mathrm{A}} = 34200 - 28728 = 5427$ N.

Upward force that piece ②-1 actually suffers is calculated according to formula (6) (Table 4):

$$f = \frac{F - G}{A} = \frac{5427}{3420 \times 1000} = 0.0016\,\mathrm{MPa}. \tag{7}$$

The tensile strength of ordinary cement concrete is very low, which is approximately 1/15 of the tensile strength, and measuring difficulty is high [18]. The tensile strength of foamed concrete of the project is around 1.5 MPa, which is lower, and measuring difficulty is higher. The fitting formulas of tensile strength at 7 d and 28 d [9] are as follows:

$$y_1 = 0.0018x - 0.6985, \tag{8}$$

$$y_2 = 0.0015x - 0.5753, \tag{9}$$

where x is the wet density of foamed concrete, and the average wet density on-site is obtained as 560 kg/m^3.

Per formulas (8) and (9), the splitting tensile strength of foamed concrete at 7 d and 28 d is calculated, respectively, as follows:

$$\begin{aligned} y_1 &= 0.0018x - 0.6985 = 0.0018 \times 560 - 0.6985 \\ &= 0.3095\,\mathrm{MPa}, \end{aligned} \tag{10}$$

$$\begin{aligned} y_2 &= 0.0015x - 0.5753 = 0.0015 \times 560 - 0.5753 \\ &= 0.2647\,\mathrm{MPa}. \end{aligned} \tag{11}$$

The tensile strength calculated per formulas (8) and (9) is 20.6 percent and 17.6 percent of its splitting tensile strength (calculated as 1.5 MPa), exceeding the proportion that tensile strength of concrete accounts for its compressive strength. Moreover, the splitting tensile strength obtained by the fitting formula at 7 d is greater than that at 28 d. This does not fit the logic and actual situation. Therefore, the reliability

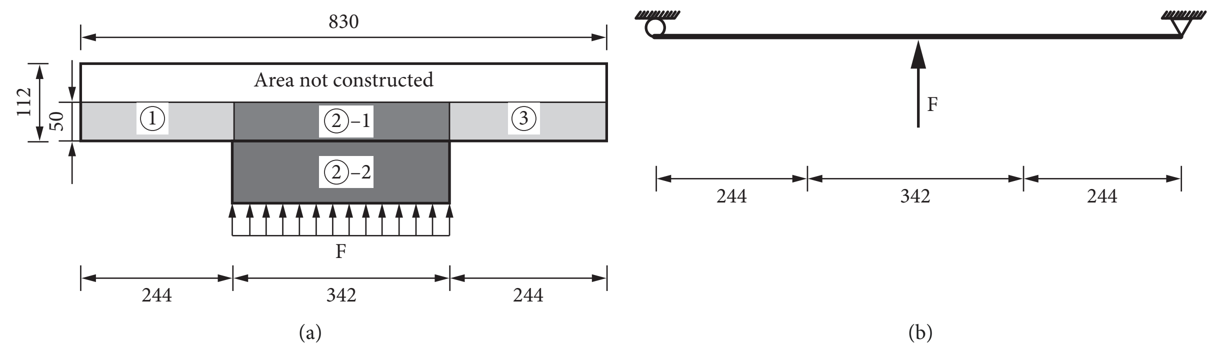


Figure 8: K59 + 520~K59 + 530: (a) simplified piece and (b) stress simplified graph.

Table 3: K59 + 520~K59 + 530: buoyance calculation of foamed concrete.

Block number	Horizontal length (m)	Vertical linear width (m)	Height (m)	Volume (m^3)	Water density (kg)	Buoyancy	Note
①	2.44	1	0.5	1.22	1000		Not calculated
②-1	3.42	1	0.5	1.71	1000	**34200**	Not calculated
②-2	3.42	1	1	3.42	1000		
③	2.44	1	0.5	1.22	1000		Not calculated

Table 4: K59 + 520~K59 + 530: upward force of foamed concrete and stress calculation.

Block number	Length (m)	Linear meter length (m)	Height (m)	Volume (m^3)	Foamed concrete density (kg/m^3)	Gravity	Upward arch force = buoyancy − gravity (N)	Actual upward stress (MPa)	Note
①	2.44	1	0.5	1.22	560	6832	Not within the scope of immersion, excluded		
②-1	3.42	1	0.5	1.71	560	9575	**5427**	**0.0016**	Transfer through block ②-2
②-2	3.42	1	1	3.42	560	**19152**			
③	2.44	1	0.5	1.22	560	6832	Not within the scope of immersion, excluded		

of fitting formulas (8) and (9) requires further study. This is closely connected with low tensile strength and difficult test measurement of foamed concrete.

The next step is to calculate fracture resistance of the simply supported beam in Figure 8(b) based on the following dynamics formula:

$$f = \frac{3Fl}{2bh^2}. \tag{12}$$

The above formula leads to

$$F = \frac{2bh^2 f}{3l}. \tag{13}$$

Using formula (13), upward force is calculated as follows:

$$F_{7\text{d}} = \frac{2bh^2 f}{l} = \frac{2 \times 1000 \times 500^2 \times 0.3095}{3 \times 8300} = 6215\,\text{N}, \tag{14}$$

$$F_{28\text{d}} = \frac{2bh^2 f}{l} = \frac{2 \times 1000 \times 500^2 \times 0.2647}{3 \times 8300} = 5315\,\text{N}. \tag{15}$$

The upward force in damage should be calculated as per formula (6):

$$f_{7\text{d}} = \frac{F_{7\text{d}}}{A} = \frac{6215}{1000 \times 3420} = 0.00155\,\text{MPa}, \tag{16}$$

$$f_{28\text{d}} = \frac{F_{28\text{d}}}{A} = \frac{5315}{1000 \times 3420} = 0.00154\,\text{MPa}. \tag{17}$$

Upward force is calculated according to tensile strength of foamed concrete collected by Cheng Guanzhi. Table 5 shows calculation results.

The comparison shows the bulge stress that piece ②-1 actually suffers is 0.00166 MPa, which is greater than the upward stress of 0.00155 MPa and 0.00154 MPa during damage that concrete can bear at 7 d and 28 d. This is the main factor causing crack on the top of piece ②-1 foamed concrete. As a matter of fact, Figure 8(a) displays that crack is likely to appear in the middle of piece ②-1 and also may appear on the block of pieces ① and ③. It can be seen from the site picture that K59 + 520~K59 + 530 demonstrates a

Table 5: Upward force of foamed concrete and stress calculation.

Maintenance time	Density	Fitting compressive strength formula	Fitting tensile strength (MPa)	Average tensile strength (MPa)	Tensile percentage	$F = (2bh^2 f)/3l$ (N)	Stress area (mm^2)	Upward stress limit (MPa)	Actual upward stress (MPa)	Conclusion
7 d	560	$y_1 = 0.0018x - 0.6985$	0.3095	1.5	20.6	6215	3420×1000	**0.00155**	**0.0016**	Crack is generated
28 d	560	$y_2 = 0.0015x - 0.5753$	0.2647	1.5	17.6	5315	3420×1000	**0.00154**	**0.0016**	Crack is generated

cross-through shake: the shorter crack appears horizontally on main through shake pieces ①, ②-1, and ③. Obviously, such tensile crack is not limited to piece ②-1, and it even extends to pieces ① and ③, showing that the upper simply supported beam of foamed concrete poured for pieces ①, ②-1, and ③ in Figure 8(a) is subject to tension. This seemingly does not fit the analysis in Figure 8(a) that only piece ②-1 suffers upward stress. In fact, the comprehensive stress of foamed concrete is complex or inflicts tension upon pieces ① and ③ due to high upward stress that piece ②-1 suffers or the high water level caused by heavy rain in summer, sometimes which may exceed the top of foam concrete, causing a greater buoyance than the value theoretically calculated. The coverage scope affects pieces ① and ③. The tension that the structure suffers is higher, and crack severity is greater than imagined. Certainly, the crack cannot eliminate combined complex force such as asymmetrical buoyance and subsurface pressure water seepage. Affected by asymmetrical buoyance and subsurface pressure water penetration, the crack also appears when exceeding bulge stress of the top of foamed concrete analyzed above.

To sum up, the foamed concrete subgrade of step shape in high groundwater table is easily subject to buoyance, causing crack on its top. In a word, design and construction unit should attach great importance to the environment of groundwater table so as to determine if foamed concrete or antifloating measures should be adopted.

4. Numerical Simulation of the Simple Structure under Concentrated Load Effect

Construction wet density and strength of foamed concrete during the test section of the project [19] are shown in Table 6. The design strength of the foamed concrete embankment is greater than 0.8 MPa. The design strength of the foamed concrete roadbed is slightly greater than 1.0 MPa, with the average wet density 560/m^3. The field sampling test indicates that the compressive strength of foamed concrete generally fluctuates from 1.3 MPa to 1.8 MPa.

The relation between elastic modulus and strength of foamed concrete per standard [20] is

$$E_c = 250 q_u, \tag{18}$$

where E_c is the elastic modulus (MPa) and q_u is the compressive strength (MPa).

By combining the project and standard [20], two groups of numerical simulations are performed: when compressive strength is 0.8 MPa, its relevant elastic modulus is 200 MPa, and when compressive strength is 1.6 MPa, its relevant elastic modulus is 400 MPa (Table 7).

The finite element model is established for the simply supported beam and continuous beam (support concretion) in Figure 8(a) using the ANSYS software. Consider meter as unit for width direction and equally divide upward force 5427 N into 11 pieces calculated in Table 4. This is equivalent to linear load imposed every one-meter extension (Figure 9). The elastic modulus 200 MPa and 400 MPa are employed, respectively, to conduct numerical simulation to analyze upward displacement and tensile stress under upward force 5427 N.

4.1. Structure When Elastic Modulus E Is 200 MPa. It can be known from Figure 10 that the span displacement of the simply supported beam in the Y direction is 24.08–27.09 mm under concentrated load and the elastic modulus of 200 MPa. The support displacement (UY) is −0.00~3.01 mm.

Figure 11 shows that, under concentrated load, the principle tensile stress of the span top is 0.29~0.34 MPa. The tensile stress of span bottom S1 is −0.01 to 0.05 MPa. The tensile stress of support 1S1 equals −0.01~0.05 MPa. The tensile stress of support 2S1 equals −0.07~0.46 MPa.

It can be known from Figure 12 that, under concentrated load and elastic modulus of 200 MPa, the span displacement of the continuous beam in the Y direction is 13.82–15.54 mm. The support displacement (UY) is −0.00 ~1.73 mm.

Figure 13 shows that the principle tensile stress of the span top is 0.23~0.27 MPa. The tensile stress of span bottom S1 is −0.01 to 0.03 MPa. The tensile stress of support 1S1 equals −0.05 to 0.31 MPa. The tensile stress of support 2S1 equals that of support 1.

4.2. Structure When Elastic Modulus Is 400 MPa. It can be seen from Figure 14 that, under concentrated load and elastic modulus of 400 MPa, the span displacement of the simply supported beam in the Y direction is 12.04–13.54 mm. The support displacement (UY) is −0.00~1.50 mm.

It can be known from Figure 15 that the span displacement of the continuous beam in the Y direction is 6.91–7.77 mm under concentrated load and elastic modulus of 400 MPa. The support UY equals −0.00~0.86 mm.

Given Figures 9–15 and concentrated load, the following conclusions are made through numerical simulation for step-shaped foamed concrete subgrade under groundwater buoyance (large at the top and small at the bottom):

(1) Displacement: in case of the same elastic modulus, the midspan of the simply supported beam is larger than that of the continuous beam. The larger the elastic modulus is, the smaller the displacement of the midspan of the simply supported beam will be. The largest displacement 27.09 mm occurs on the top of the simply supported beam when elastic modulus is 200 MPa; namely, upward deflection at this point may reach up to the maximum value 27.07 mm.

(2) First principal stress: in case of the same elastic modulus, the top of the simply supported beam midspan is larger than that of the continuous beam midspan. With elastic modulus increased, the tensile stress of the simply supported beam demonstrates no changes, and so does the continuous beam. The maximum tensile stress is 0.34 MPa, which occurs on the top of the simply supported beam when elastic modulus is 200 MPa and 400 MPa, respectively.

Table 6: Construction wet density and strength of foamed concrete.

Distance from the top of foamed concrete (m)	Construction wet density (kg/m^3)	Compressive strength at 28 d (MPa)
0~1.2	550	1.0
>1.2	500	0.8

Table 7: Value reference and analysis content of numerical simulation.

Group no.	Fitting elastic modulus (MPa)	Fitting compressive strength (MPa)	Lower limit of design compressive strength (MPa)	Typical value of site compressive strength (MPa)	Structure form	Analysis content	Note
1	200	0.8	0.8	—	Simply supported beam	Displacement	Simple support at the end
					Continuous beam	Tensile stress	Concretion at the end
2	400	1.6	—	1.6	Simply supported beam	Displacement	Simple support at the end
					Continuous beam	Tensile stress	Concretion at the end

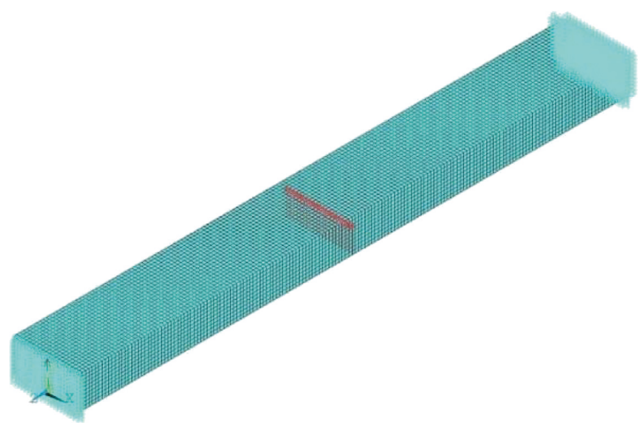


Figure 9: Finite element model ANSYS established for Figures 8(a) and 8(b).

(3) Under different elastic modulus, the maximum value of principle tensile stress of the simply supported beam midspan is 0.34 MPa, which is greater than the tensile stress 0.31 MPa obtained by fitting formulas (7) and (8). This means that crack is inevitably generated on the top of the simply supported beam. Under different elastic modulus, the principal tensile stress on the top of the continuous beam midspan is 0.27 MPa, which is similar to the tensile stress 0.26 MPa obtained by fitting formula (8). The top of the continuous beam midspan may not produce crack. However, crack is seen on the top of foamed concrete site, so the simply supported beam better fits the practical situation.

5. Measures Preventing Through Shake on Foamed Concrete Subgrade

The foamed concrete subgrade, particularly the step-shaped section, is easily subject to buoyance in high groundwater table, and such buoyance would be transferred to the top that causes crack on the top of foamed concrete. The compressive strength of foamed concrete is extremely low, and its tensile stress is weaker; consequently, through shake appears on its surface. Then, how to solve this tricky issue becomes quite pressing for the subgrade.

(1) It is suggested that foamed concrete should be less used or not used at the area where surface water or groundwater table is high. The foamed concrete is prohibited to be used at the groundwater seepage environment where pressure is high. The pressure water seepage not only easily causes subgrade floating and through shake but also may permeate into the inner structure of foamed concrete, reducing its mechanical property and weakening durability as a result.

(2) The groundwater is observed at the bottom after the foundation pit is excavated. The measures should be used to drain or lower groundwater, to ensure that construction of foamed concrete subgrade is performed with water being completely removed.

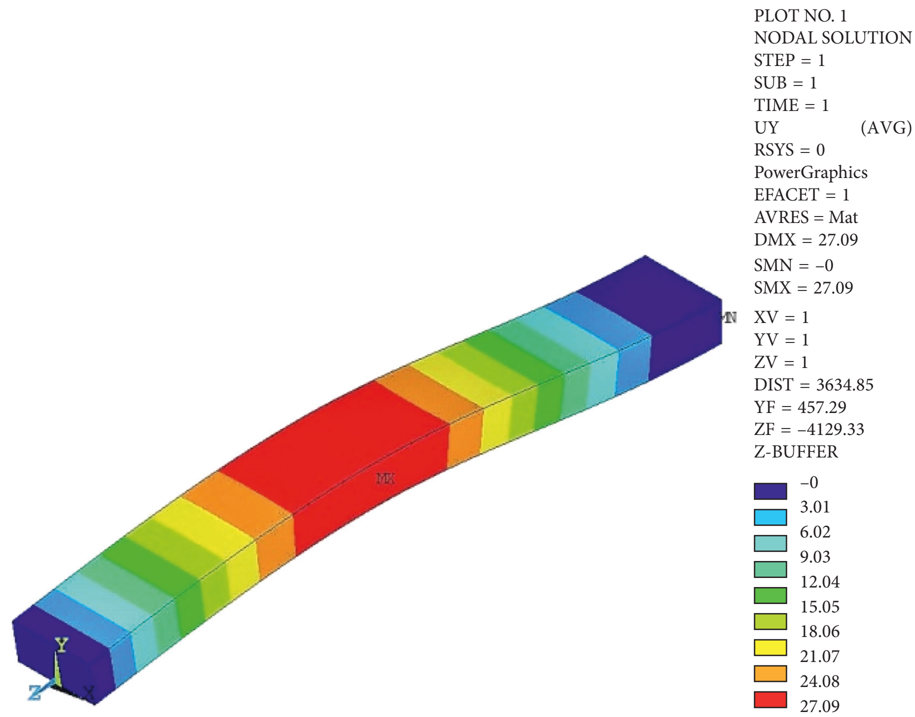


Figure 10: Displacement picture of the simply supported beam in the Y direction when elastic modulus is 200 MPa.

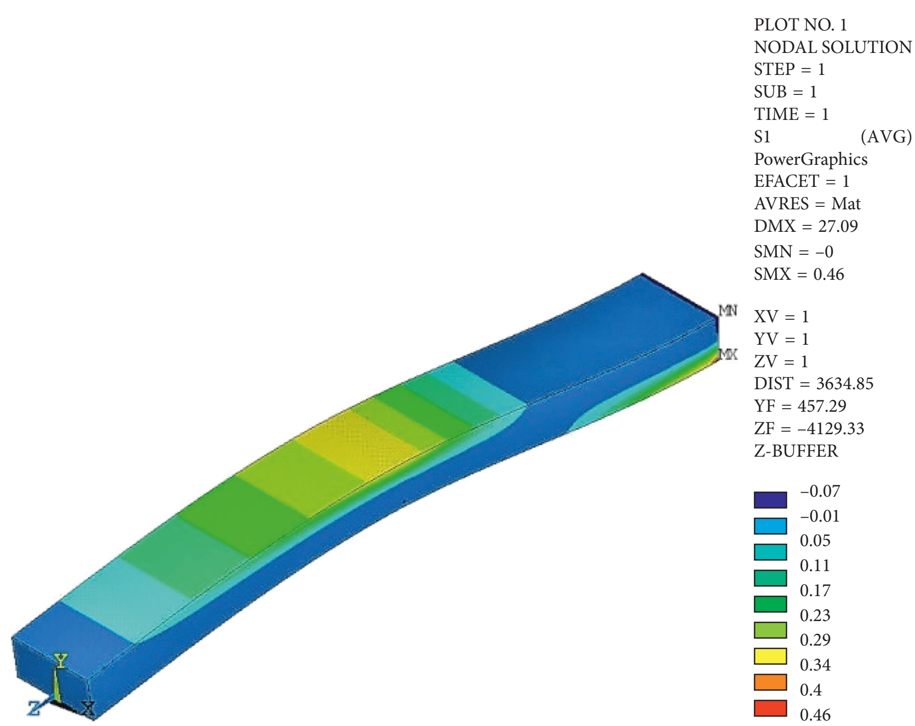


Figure 11: First principle stress of the simply supported beam in case elastic modulus is 200 MPa.

(3) For areas where surface water or groundwater table is high, the most important work is the relevant antibuoyance measure that should be adopted regardless of foamed concrete subgrade performed in a dry place. The antibuoyance measures are not fixed, which can be determined based on the practical situation. The measures could be specific to early stage or later stage and also could be decided by design, or prepared during concrete composition test, or also during construction. The early stage refers to the measures

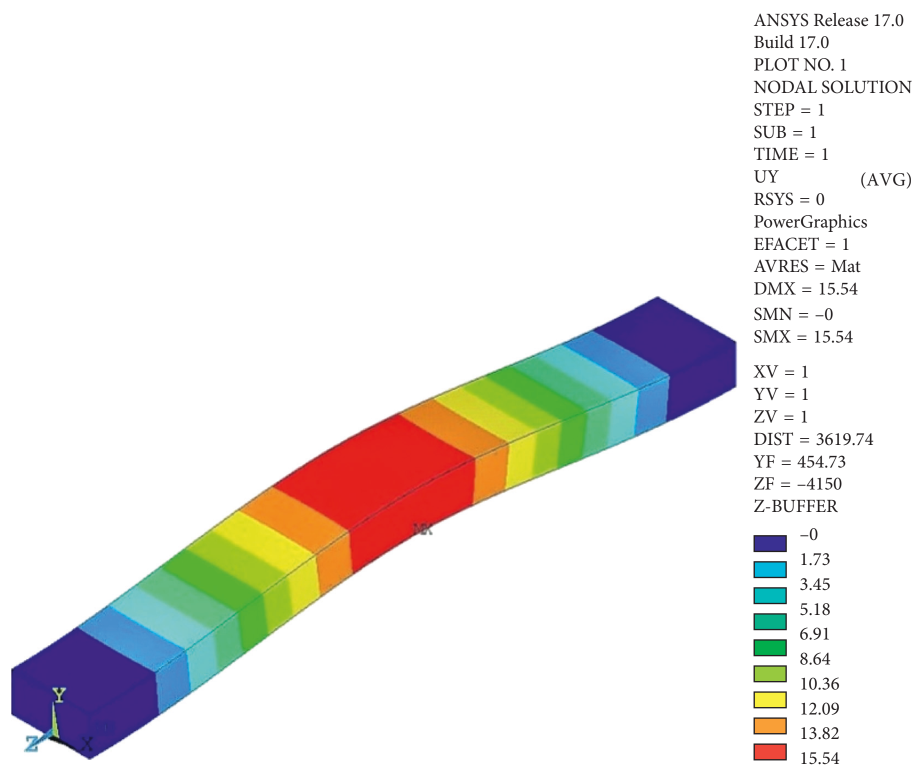


Figure 12: Displacement picture of the continuous beam in the Y direction when elastic modulus is 200 MPa.

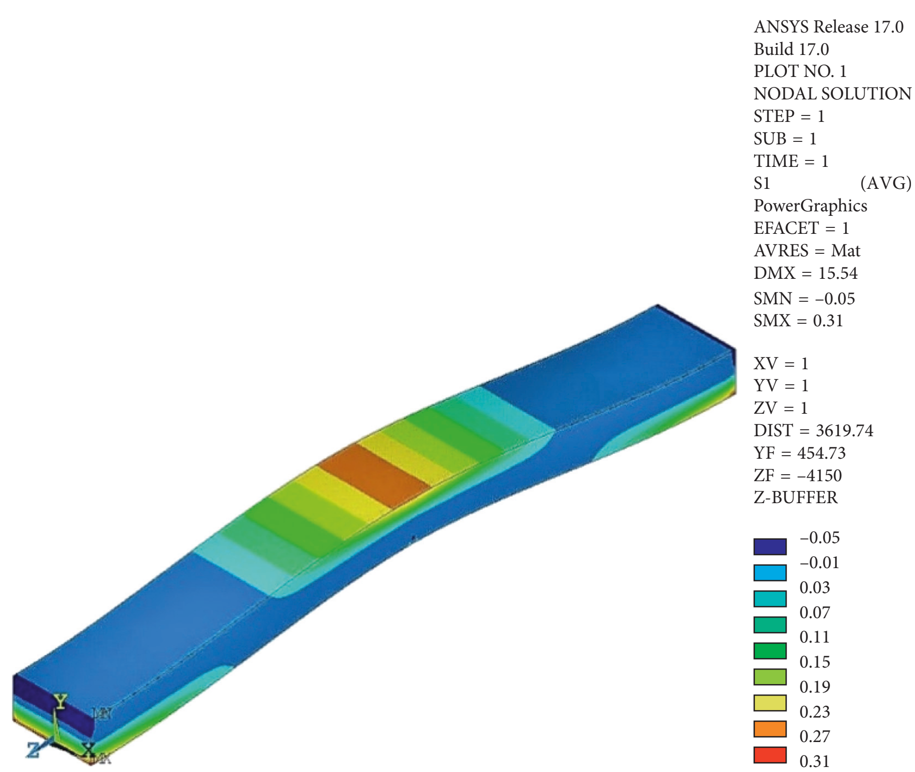


Figure 13: First principle stress of the continuous beam in case elastic modulus is 200 MPa.

taken before construction of foamed concrete. The later stage refers to measures adopted after construction. The measures decided by design mean that design specifies intercepting ditch, sump pit, and lowering groundwater to 0.5 m below foundation. The steel angle and steel mesh can also be equipped. After

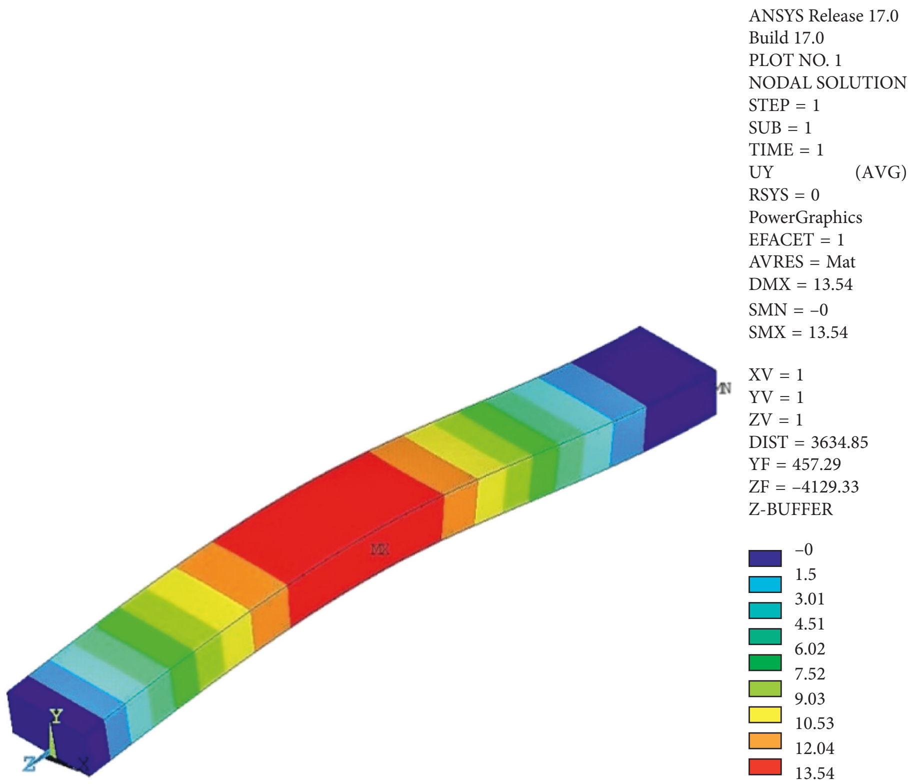


Figure 14: Displacement picture of the simply supported beam in the Y direction in case elastic modulus is 400 MPa.

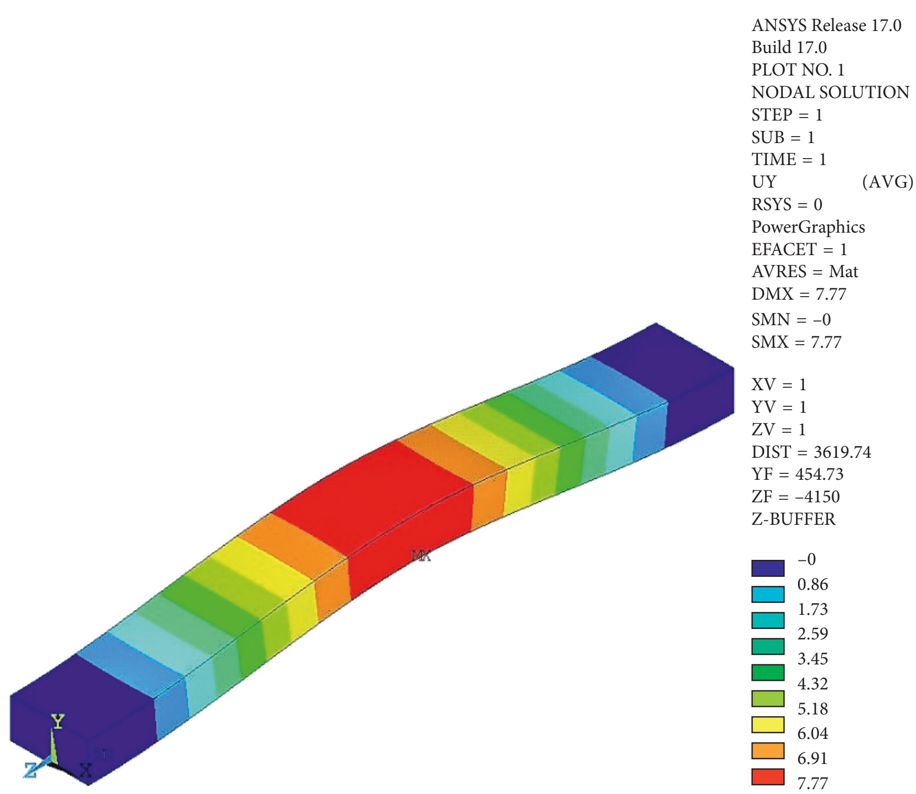


Figure 15: Displacement picture of the continuous beam in case elastic modulus is 400 MPa.

steel angle is knocked into the base of a certain depth, foamed concrete is held to prevent it from floating by means of friction resistance among steel mesh, steel angle, and foamed concrete so as to shorten size difference of upper and lower stages (Figure 16). The measures prepared during concrete composition test

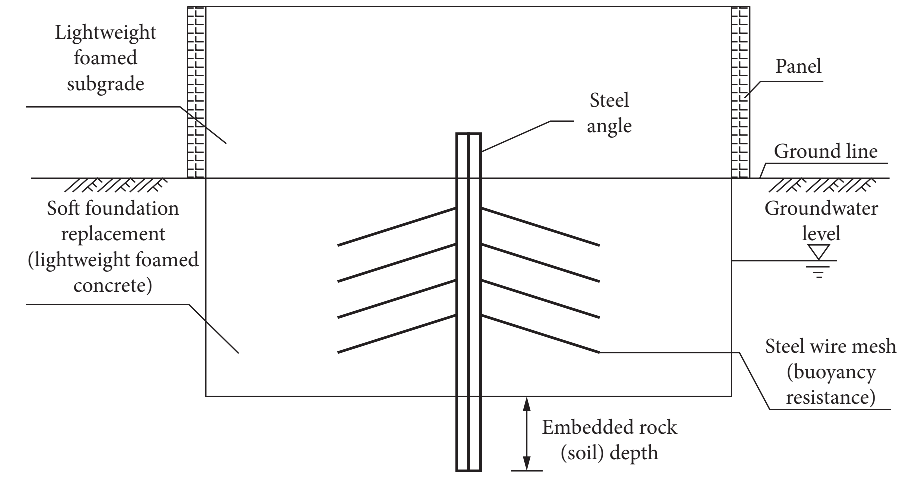


Figure 16: Steel angle and steel mesh adopted in design to keep foamed concrete from floating.

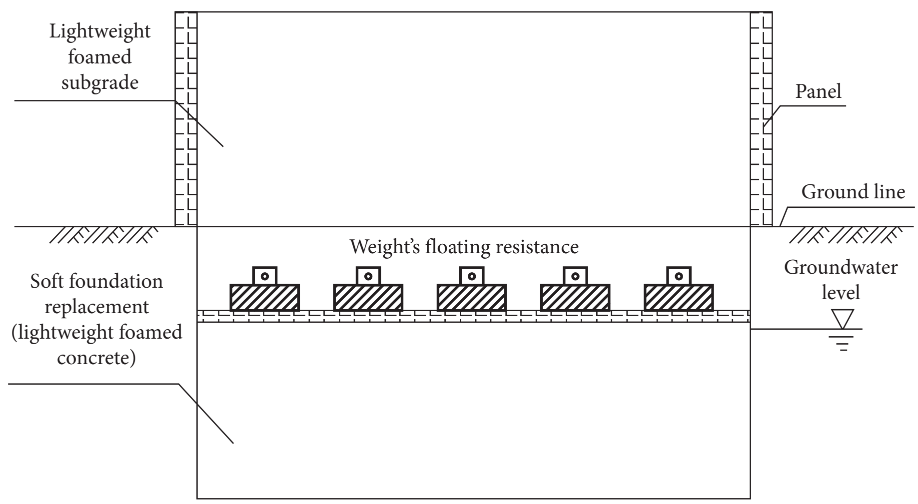


Figure 17: Weights temporarily piled on top of water.

mean that the test person can consider increasing wet density of foamed concrete during composition design, allowing foamed concrete to be close to water density in a bid to reduce floating possibility. The measures adopted during construction mean that the construction unit can consider the measures such as excavating intercepting drain and sump pit. The measures including placing weights on the top of foamed concrete can be considered (Figure 17). Also, the construction of the upper bearing layer, road base, and road top surface can be quickly performed so that road density will be far greater than that of foamed concrete. Furthermore, the road surface has substantial thickness which is equivalent to placing heavy and balanced stuff at the top of foamed concrete. Therefore, other antibuoyance measures are temporary, while this measure is long-lasting.

6. Conclusions

By performing example analysis, theoretical analysis, and numerical simulation to the through shake on the right foamed concrete subgrade at K59 + 520~550, the following conclusions can be drawn:

(1) In the environment where groundwater table is high, the step-shaped foamed concrete subgrade is subject to minor buoyance, which easily causes irregular through shake on its top.

(2) Under concentrated load, the displacement demonstrates a rule that, in the event of same elastic modulus, the midspan of the simply supported beam is larger than that of the continuous beam. The larger the elastic modulus is, the smaller the simply supported beam midspan is. The largest displacement 27.09 mm occurs at the top of the simply supported beam when elastic modulus is 20 MPa; namely, upward deflection may attain the maximum value 27.07 mm.

(3) Under concentrated load, first principal tensile stress shows a law that, in case of same elastic modulus, the top of the simply supported beam is larger than that of the continuous beam. With elastic modulus being increased, the tensile stress of the relevant simply

supported beam shows no change, and so does the continuous beam. The maximum tensile stress 0.34 MPa occurs at the top of the midspan of the simply supported beam when elastic modulus is 200 MPa and 400 MPa, respectively.

(4) Under concentrated load, the principal tensile stress is 0.34 MPa, which is greater than the tensile stress 0.31 MPa obtained by the fitting formula. This means that the crack is bound to appear at the top of the midspan of the simply supported beam. The top of the foamed concrete site shows crack, so the simply supported beam better fits the practical situation.

(5) In the environment where surface water is abundant or groundwater table is high, water should be drained firstly and groundwater be lowered to ensure that construction of foamed concrete is performed in a dry place. Meanwhile, relevant antibuoyance measures should be adopted before construction of the upper bearing layer to avert through shakes on the top of foamed concrete.

The study has expanded the application scope of subgrade and enriched theory of foamed concrete filled in high groundwater table, providing a significant reference to similar projects.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Xianbin Huang and Chenyang Liu contributed to the work equally and should be regarded as co-first authors.

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