The Effect of Vegetation Transpiration on the Deformation of High Void Ratio Expansive Soil Foundation

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ABSTRACT

Vegetation transpiration may significantly decrease the moisture content of active soils causing soil shrinkage and deformation. Severe damage to engineering structures may result. This phenomenon has been identified in reports from South Africa, Australia, and China as a cause of structural damage. This paper contains analyses of data collected in Mengzi County and other regions in China. The relationship between vegetative transpiration rates and deformation of high void ratio expansive soils is examined, and a formula for calculating estimated maximum contraction is presented. Also, current practices for dealing with active soils are discussed.

DAMAGE TO ENGINEERING

Plants that cover the earth surface are termed vegetation. Water and nutrients are assimilated by the plant root system and delivered to the leaf surface, stems, and other plant parts via capillary tubes. Only 1 percent of the absorbed water is consumed for the growth of the plants; the balance is dispersed into the atmosphere in the form of vapor by stomata on the leaf surface.

This process of water evaporation through the plant organ is called transpiration. It is shown by the measured data that different types of trees have different transpiration rates (Table 1). Among the more common trees, the jarrahs have the greatest transpiration.

Used as one of the measures to lower the groundwater table in Australia, the jarrahs are often compared to pumps. In some regions, because of the large loss of water from the foundation soil, which was caused by the transpiration of jarrahs, irregular shrinkage deformation of the foundation occurred. This caused serious engineering failures to take place.

Investigation indicated that in the expansive soil regions of Yunnan and Guangxi Province, China, building damage phenomena due to the vegetation effect are rather common (Table 2).

In these regions, building damage rates in places with growing trees are higher than in places without trees, which obviously shows the close relationship between building damage and vegetation. In Mengzi, for example, most buildings on expansive soil foundations not surrounded by trees remained in good condition. Only slight damage caused by uneven expanding and shrinking deformation of the foundation soil occurred. The deformation amplitude is not more than 15 mm and the width of wall crack is less than 10 mm. However, 90 percent of the buildings close to jarrahs and grevillea were seriously damaged. The maximum deformation amplitude of foundations of buildings near trees is up to 187.2 mm, and the

TABLE 1 Transpiration of Common Species of Trees

	Jarrah	African Eucalyptus	Grevillea	Glossy Privet	Chinese Parasol	Barren Land
Transpiration kg/day						
South Africa	1,090	454	342		61.2	0.54
Mengzi		432		68		

TABLE 2 Investigative Data of Houses Destroyed by Vegetation Influence

				Tree-Growing Site			Non-Tree Site		
Region	No. Houses Investigated	No. Houses Destroyed	Rate Destroyed (%)	No. Houses Completed	No. Houses Destroyed	Rate Destroyed (%)	No. Houses Completed	No. Houses Destroyed	Rate Destroyed (%)
Mengzi	145	109	75.1	9	100	91.7	27	9	25.0
Jianshui	56	44	78.5	4	17	80.9	8	27	77.1
Ningming	53	35	66.0	3	30	90.9	15	5	25.0
Nanning	46	25	54.3	13	21	61.7	8	4	33.3
Gui County	79	39	49.3	30	28	48.2	9	12	57.1
Yanshan	42	25	59.5	3	12	80.4	14	13	48.1
Kunming	34	20	58.8	2	12	85.7	12	8	40.0

maximum width of wall crack is 240 mm. Partial wall inclination reaches 18.9 percent (Table 3). In this area the greater the afforestation the more serious the damage. In the vicinity of the trees, structural walls nearest the trees exhibit cracks, deformation, or foundation damage.

A 36-m long, single-story building with a jarrah near one end of the front wall and no other trees nearby experienced partial shrinkage of the foundation soil near the tree. The brick work was twisted, the side line and foundation beam of the back wall was bent in the form of an arc with the tree as a circle center and the brick side line of the front wall squeezed in undulation form (Figure 1). Figures 2-6 show the damage to houses under the influence of trees. These figures also show the corridor brick pillar of some houses displaced 10 cm horizontally toward the trees. Figure 7 shows the depth of the tree roots near the houses. In some houses, reinforced concrete foundation beams with 40 x 40 cm^2

FIGURE 3 Crack on gable of building near jarrah.

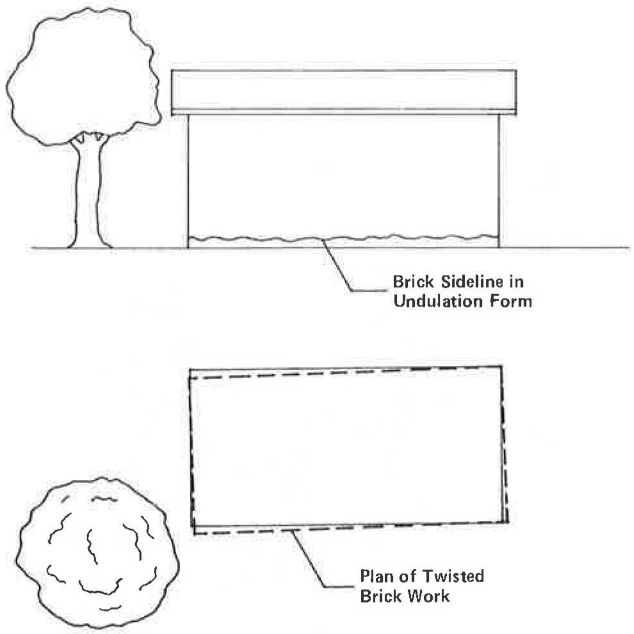

FIGURE 1 Orthogonal projection of twisted house near jarrah.

FIGURE 4 Inclination of external wall.

FIGURE 2 Horizontal displacement of corridor brick pillar.

FIGURE 5 Collapse of roof.

TABLE 3 Statistical Data of the Relationship Between Building Deformation and Vegetation

Building No.	Foundation Type	Embedded Foundation Depth (m)	Construction Type
I-5	Strip footing on sand cushion	1.50	Brick and wood, one-story
I-7	Pier foundation	1.20	Brick and wood, one-story
II-1	Pier foundation	3.95	Brick and concrete, three-stories
II-3	Pier foundation	3.95	Brick and concrete, three-stories
II-5	Pier foundation	3.95	Brick and concrete, three-stories
II-2	Pier foundation	3.95	Brick and concrete, three-stories
II-20	Strip footing	0.80	Brick and concrete, one-story
II-16	Pedestal pile	3.00	Brick and concrete, two-stories
IV-6	Strip footing	0.80	Brick and concrete, two-stories
Jiang-shuidi Hotel	Strip footing	0.80	Brick and concrete, one-story
I-Auditorium	Strip footing	0.80	Brick and wood
III-24	Strip footing	0.80	Brick and wood, two-stories

[a] Due to the high solid rigidity of building no crack occurred.

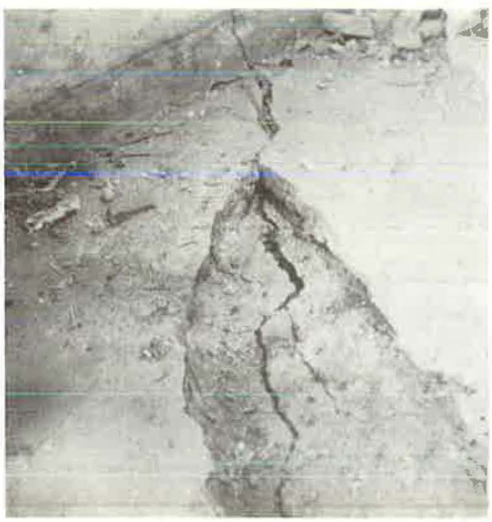

FIGURE 6 Breakage of foundation and foundation beam caused by crack through soil under foundation.

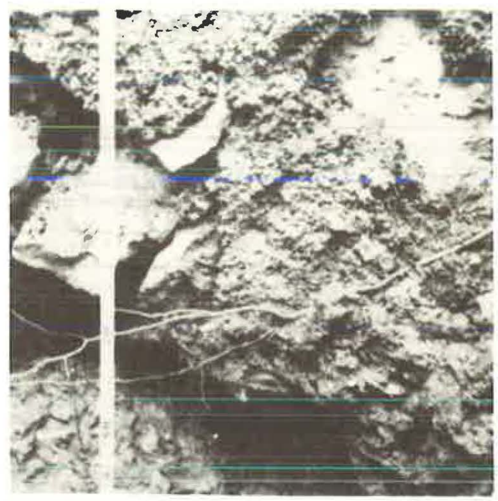

FIGURE 7 Extended depth of tree roots, which is equal to the height of the tree and observed from the excavated cross section.

cross sections were broken by stretching. Some roofs caved in, exposing the rooms to the sky, and some external walls collapsed. Many houses collapsed without demolition. The remaining houses were no longer usable. They had suffered damage as severe as that caused by an earthquake.

FOUNDATION DEFORMATION

Vegetation transpiration causes water loss of foundation soils and forms a limited shrunken section--the main reason that adjacent buildings suffer differential settlement of foundation elements. The data observed in the Mengzi region indicated that the lower limit of water content variation of foundation soil is low in an area influenced by jarrahs, and the water content variation is wide. The amplitude between expansive and deformation is substantial. At a shringage depth of 3 m, amplitude of water content variation of foundation soil in forest zones is 2 to 3 times that in barren land, and the deformation amplitude is 8 to 20 times as great (Table 4). It is evident that the effect of vegetation transpiration on foundation soil is greater than the effect of weather evaporation.

In vegetated areas, foundation deformation is related to seasonal weather variations. Measuring mark deformation curves show regular variation as they move upward in the rainy season and downward in the dry season (Figure 8). The measuring mark of those that drop greatly also rise significantly. Those that drop slightly rise only slightly. This indicates that the foundation soil experiences reversible expansive and shrinking deformation, which alternate endlessly as humidity and soil moisture increase and decrease. Because the observed contraction of foundation soil was greater than the expanding deformation in a period of 1 1/2 yr, the curve of relationship between measuring mark and time inclines downward continuously, and the maximum sinking value at 1 m depth is up to 128 mm. Elimination of the tree roots causes the curve to rise continuously. In 8 months the rising amplitude

Effect

Vegetation Condition	Distance to Tree (m)	Maximum Deformation Amplitude Near Tree (mm)	Maximum Deformation Amplitude (mm)	Building Condition
Non-tree			7.6	Good
Non-tree				Good
Non-tree				Good
Non-tree			11.4	Good
Rows of jarrahs	5-8	35.0		2.94 percent inclined to direction of tree[a]
Rows of jarrahs	8-10	69.2		6.6 percent inclined to direction of tree[a]
Rows of jarrahs	3-10	83.1		Medium damage, wall crack width 3-5 cm
Rows of jarrahs	3-5	46.8		Slight damage, wall crack width 2-5 cm
Independent jarrah	3-6	187.2		Serious damage, wall crack width 8-20 cm
Rows of jarrahs	3-5	66.8		Medium damage, wall crack width 2-3 cm
Rows of jarrahs	3-2			Serious damage, gable and roof truss collapse
Rows of jarrahs	3-5			Serious damage, gable and roof truss collapse

TABLE 4 Jarrah Deformation Amplitude—Forest Area and Barren Land

	Depth (m)									
	Barren Land, 1.0	Forest Area, 1.0	Barren Land, 1.5	Forest Area, 1.5	Barren Land, 2.0	Forest Area, 2.0	Barren Land, 2.5	Forest Area, 2.5	Barren Land, 3.0	Forest Area, 3.0
Water content										
Rainy season	36	38	36	38	37	36	41	41	39	37
Dry season	32	26	30	26	31	26	35	30	35	29
Amplitude of variation	4	12	6	12	6	10	6	11	4	8
Deformation amplitude of measuring mark, mm	12.6	105.1	11.9	99.1	7.7	96.2	3.8	74.5	3.2	42.8

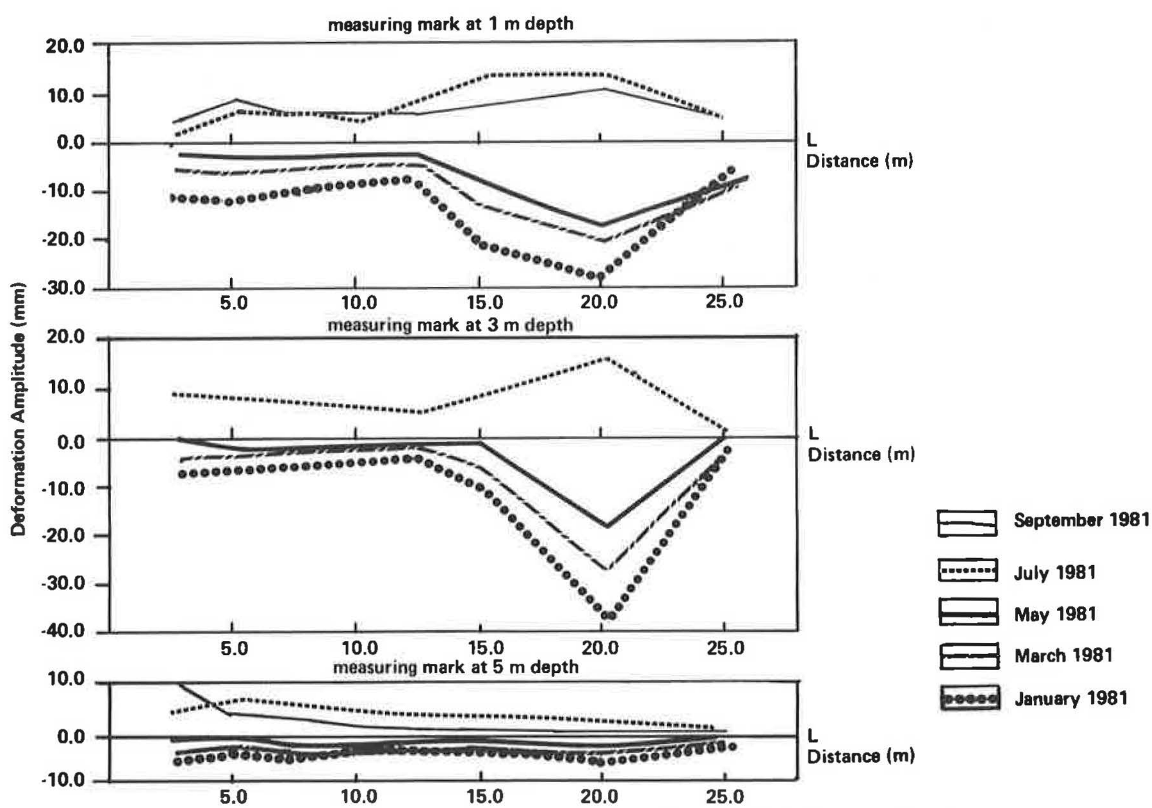

FIGURE 8 Deformation curves of measuring marks at different depths under the influence of jarrahs.

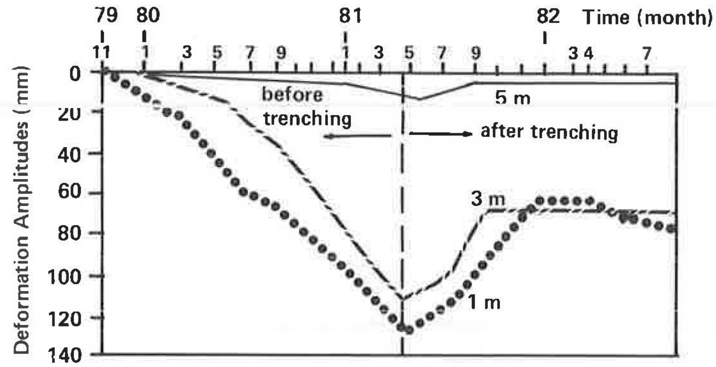

FIGURE 9 Curve of relationship between measuring mark and time.

reached 66 mm (Figure 9). The reversible deformation character of the expansive foundation soil and the formation of partial "dry shrunk area" of the foundation soil caused by vegetation transpiration were obviously indicated by the previously mentioned effect of return rising.

Vegetation transpiration unbalanced the water condition in the soil, thus causing the formation of a new humidity field as well as humidity variation within the foundation soil in the dry shrunk area (Figure 10). Therefore the water suction ability of the foundation soil matrix also varied. Because of this difference, the water in the soil transfers continuously to the tree roots. After cutting a lime trench between the house and tree in the jarrah-affected area, both the C and D measuring mark groups at the side of the house had 2 yr rising deformation, whereas sinking deformation occurred on the A and B measuring mark groups (Table 5 and Figure 11). On the house side, transfer of the soil water to the tree had been stopped after separation of the foundation soil from the influence of the tree roots. Before trenching, the water content of the foundation soil inside the house was 31 percent, after trenching it increased to 41 percent. Thus, the C and D measuring mark groups rose rapidly, and the D group, which was inside the house, had the largest rising amplitude--the maximum rising rate reached 40 mm/month. On the tree side, due to the decrease of dry shrunk area, water consumption from the foundation soil for vegetation transpiration increased, and the foundation soil showed substantial deformation.

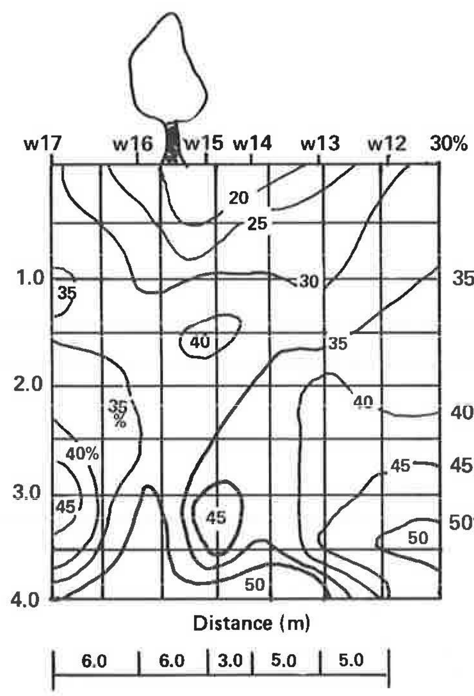

FIGURE 10 Humidity isogram of jarrah influence area.

In the foundation soil affected by the tree, the sphere to be bounded within the deformation-influenced radius horizontally and depth vertically is called dry shrunk area. Its scope depends on the species, age, trunk diameter, and root growing condition of the trees. In the Mengzi region, a growing jarrah 10 yr old with a 20- to 40-cm diameter trunk caused the ground surface to be deformed with 15 to 37 mm amplitude, and it has an influence sphere of about 8 m radius (Figure 12). A deformation curve of 72 measuring marks in different depths near a fully grown jarrah 17 m high with a trunk diameter of about 50 cm shows that deformation differential of measuring marks in different parts of the dry shrunk area is great (Figure 13). It was discovered after excavation that the humidity of the part of the foundation soil where the tree hair reaches varies greatly as well as the deformation amplitude (Figure 7). The deformation amplitude of the measuring mark with distance to tree beyond 25 m was obviously reduced and nearly equal to the deformation amplitude of measuring mark in the area free of trees. This indicates that the deformation-influenced radius under the jarrah is 25 m, which approximately equals 1.4 times the tree height. As a rule the deformation amplitude of measuring mark in the dry shrunk area decreases progressively with the increase in depth (Figures 8 and 13). Assuming the depth of measuring marks with deformation amplitude $\leq$ 10 mm to be the tree-influence depth, the influence depth of jarrahs in the dry shrunk area is 3.5 to 8 m. The farther the spot from the tree, the smaller the influence depth will be (broken line in Figure 14). The influence depth measured from the mark with 25 m distance from the tree is 3.5 m. This is similar to the weather influence depth in space without trees.

INFLUENCE FACTORS

As mentioned previously, the main factor that affects the foundation soil deformation in vegetation areas is vegetation transpiration and the expanding and shrinking character of the soil. Beyond the species of tree, the amount of transpiration is

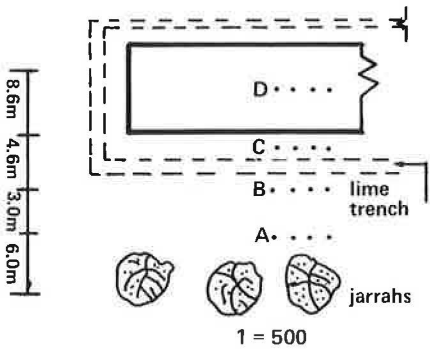

FIGURE 11 Location of measuring marks at different depths on both sides of lime trench.

related to the local weather in addition to the restrictions of the hydrogeology and engineering geology condition of the site. Rothenberg believes that the relative humidity of the environment can restrain vegetation transpiration (1). The higher the relative humidity, the lower the vegetation transpiration.

Thus, the effects of vegetation transpiration on deformation of foundation soil in humid climates are smaller than in dry climates. The effects of vegetation transpiration on water content variation and deformation of foundation soil are small on the site that has a thick earth cover or a high groundwater table. But on the site that has a thin earth cover and a low groundwater table, because of the transpiration influence caused by water suction of the tree root, the water loss of the foundation soil is

TABLE 5 Deformation Amplitude of Measuring Marks at Both Sides of Lime Trench

Measuring Mark Deformation (mm), Depth (m)	Group A			Group B			Group C			Group D		
	Rising	Sinking	Amplitude	Rising	Sinking	Amplitude	Rising	Sinking	Amplitude	Rising	Sinking	Amplitude
1.0	0.0	-21.2	21.2	0.0	-22.6	22.6	9.3	0.0	9.3	43.2	0.0	43.2
2.0	0.0	-21.1	21.1	0.0	-17.5	17.5	9.0	0.0	9.0	23.4	0.0	23.4
2.5	0.0	-13.0	13.0	0.0	-10.8	10.8	6.8	0.0	6.8	10.4	0.0	10.4
3.0	0.0	-8.8	8.8	0.0	-5.3	5.3	4.2	-1.1	5.3	8.4	0.0	8.4

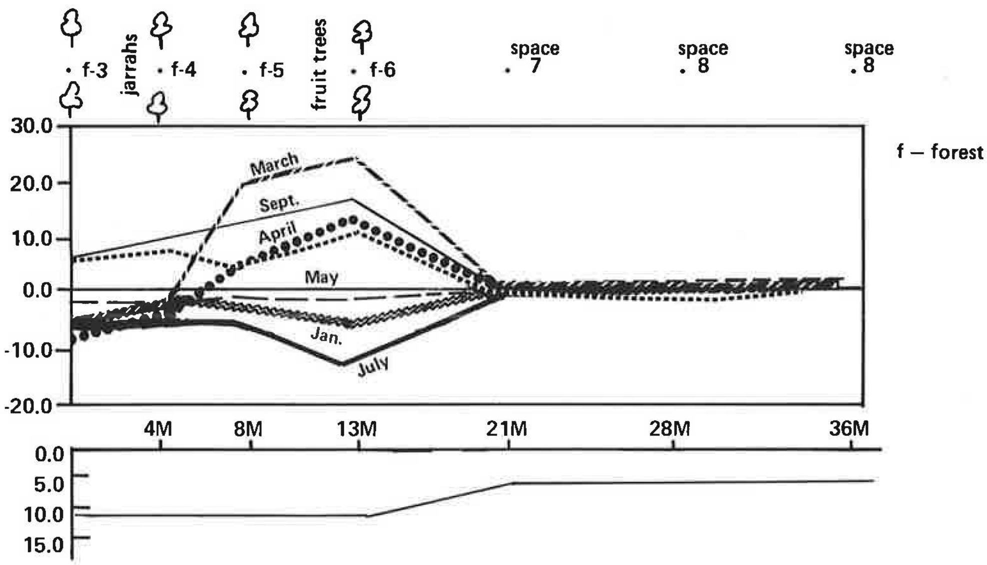

FIGURE 12 Observed cross section of surface deformation near jarrahs in Mengzi region.

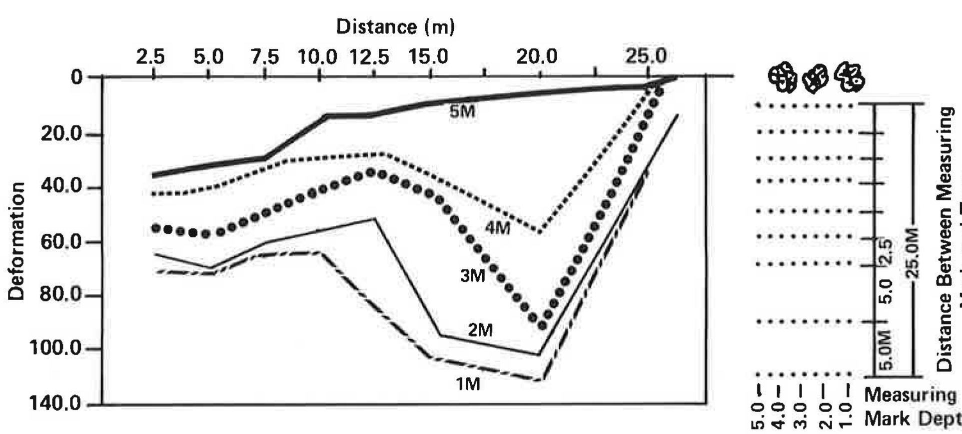

FIGURE 13 Relationship between deformation amplitude of measuring mark and distance to tree.

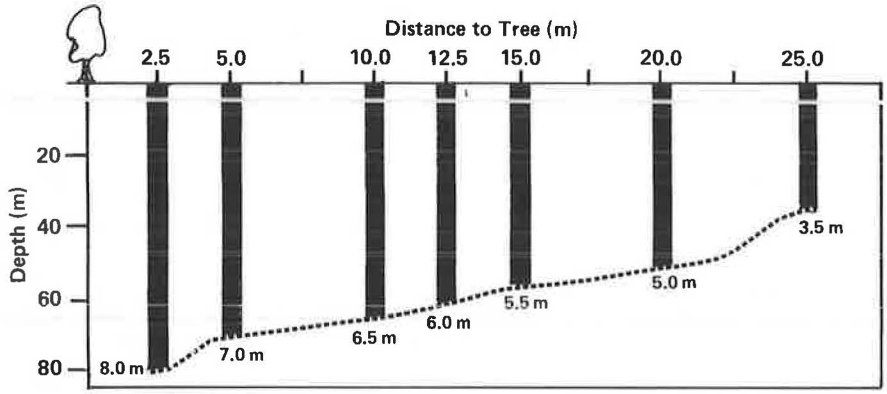

FIGURE 14 Influence depth of measuring marks at different distances to tree.

high; therefore, substantial shrinking deformation can easily occur.

It should be pointed out that vegetation transpiration is an external factor that causes the humidity variation of the foundation soil. Only the expanding and shrinking character of the soil is the essential factor of deformation of foundation soil. Under the influence of vegetation transpiration, the foundation soil with high void ratio and strong expanding character will have a low lower limit of water content variation and remarkable shrinking deformation. For example, in the Mengzi region, the humidity coefficient of foundation soil is Km = 0.6, free expansion ratio is e_{FS} = 81 percent, and the natural void ratio is e_o = 1.15. Because of the small humidity coefficient of foundation soil, dry weather, high vegetation transpiration, as well as high void ratio and strong expanding character, the effect of vegetation on deformation of foundation soil in the Mengzi region is rather great (Tables 3 and 4).

The deformation amplitude of measuring marks adjacent to the tree is up to 105.1 mm, that of parts of the house close to the tree reaches 187.2 mm. In this same area, however, the nonexpansive foundation soil is e_{FS} = 30 percent and e_o = 1.41, and the deformation amplitude of measuring marks near the jarrah at a 1-m depth is only 30 mm.

Hefei has a subhumid climate (Km = 0.8, e_{FS} = 64 percent, and e_o = 0.65); deformation amplitude of parts of the house near the tree is 7.82 to 11.3 mm. In the Chengdu area (Km = 0.9, e_{FS} = 61 percent, and e_o = 0.64), deformation amplitude of parts of the house close to the tree is 18 mm. This value is approximately equal to the deformation amplitude of an area without trees; therefore it is evident that the deformation of foundation soil is not affected by the tree. It is evident from the preceding examples that the deformation of foundation soil is related to Km in inverse ratio and to e_o in direct ratio. Therefore the effect of vegetation on buildings with high void ratio expansive foundation soil is remarkable in dry and sub-dry regions in China.

The possible shrinkage rate (S_1) of the foundation soil under the influence of weather and soil character may be calculated from the formula given below when the following conditions are satisfied:

1. Foundation soil is beyond the influence of groundwater and $e_{FS} \geq$ 40 percent; and
2. Deformation of foundation soil refers to the shrinkage that is caused by the decrease of water content, and the void ratio variation of soil is in direct proportion to the variation of water content.

$$S_1 = e_o - e_m / 1 + e_o \times 100\%$$

where

S_1 = possible shrinking deformation rate at 1-m depth of foundation soil because in measuring on-site the greatest deformation is obtained at 1-m depth in the vegetation area; therefore, only the deformation amplitude of foundation soil at 1-m depth is calculated, and the average rate of deformation within the 1-m depth of foundation soil is taken for calculating rate;
e_o = natural void ratio of soil;
e_m = void ratio of soil in which water content is minimum W_m, $e_m \approx 0.028 W_m + 0.041$ may be taken in lack of measuring data, and
W_m = minimum water content that depends on character of soil, weather, and humidity of foundation (2).

Possible shrinkage rates of foundation soil in 40 places in regions with high vegetation transpiration have been calculated according to the preceding formula. The results are compared with the actual destroyed condition of the corresponding houses. The following conclusions can be drawn: in areas in which S_1 is inversely proportional to Km and directly proportional to e_o, Km $\geq$ 0.9, $e_o \leq$ 0.7, or S_1 < 10 percent, damage is not a result of vegetation; in areas in which Km < 0.9, e_o > 70.7, or $S_1 \geq$ 10 percent, damage to the houses is related to the vegetation, and the greater the S_1, the greater the vegetation's influence (Table 6 and Figures 15, 16). Thus the conclusion may be drawn that S_1 may be used as a quantitative index in predicting and estimating the effect of vegetation on foundation soil deformation. In the area in which $S_1 \geq$ 10 percent, the possible engineering damage caused by the influence of trees with high transpiration should be taken into account, whereas in the area in which S_1 < 10 percent the influence of trees can be discounted.

TREATMENT

The vegetation influence presenting measurements and afforestation experience in Mengzi and other regions can be summarized as follows:

1. When building houses in areas expected to be influenced by vegetation, the general layout should be planned rationally with the buildings laid out beyond the tree influence radius, and light transpiration trees should be selected for afforestation (see Table 3).
2. A lime trench may be dug between the house site and the tree before construction to create a

TABLE 6 The Calculated Foundation Soil Shrinkage Rate of Different Regions

	Region													
Index	Mengzi	Panxi	Kunming	Qujing	Wenshan	Ningming	Yun County	Linyi	Gui County	Hefei	Jingmen	Chengdu	Nanjing	Nanning
e_{FS} (%)	81	64	62	80	52	68	53	61	50	64	64	61	57	56
I_p	34	25	32	28	27	29	22	29	35	23	24	21	21	29
K_m	0.60	0.60	0.70	0.70	0.70	0.74	0.74	0.76	0.80	0.80	0.80	0.90	0.90	0.87
e_o	1.15	1.04	1.16	1.13	1.21	0.79	0.63	0.83	0.92	0.65	0.60	0.64	0.65	0.89
e_m	0.70	0.63	0.67	0.59	0.71	0.58	0.56	0.59	0.76	0.54	0.51	0.57	0.55	0.70
S_l	21.0	20.0	22.7	25.0	22.6	11.7	4.3	13.1	8.3	6.7	5.6	4.3	6.1	10.0
	*	*	*	*	*	*	+	+	*	+	+	+	+	*

Note: Mark "*" means damage to houses is related to tree influence. Mark "+" means damage is not a result of tree influence.

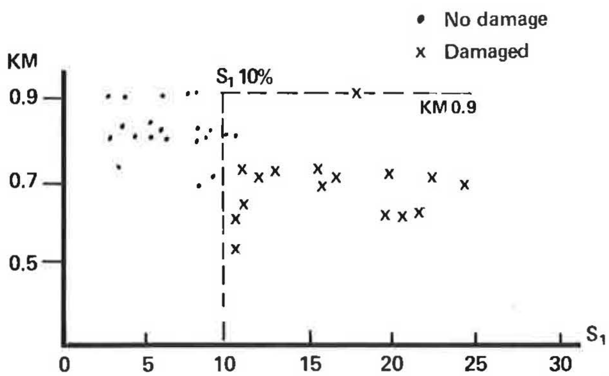

FIGURE 15 Relationship between Km and S_1.

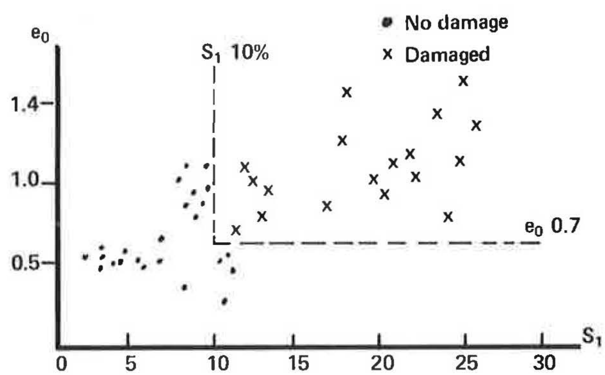

FIGURE 16 Relationship between e_o and S_1.

moisture transfer barrier. The depth of the trench should be 2 m and the length should be equal to the tree influence radius. One side of the trench should be filled with lime to the ground surface; the thickness of the lime fillings should be 10 to 20 cm. The other side of the trench, after having been filled with earth, should be rammed and sealed with cement (Figure 17). Whether using this method or cutting down the tree to build the house, the land should not be used for construction for 0.5 to 1 yr. The house cannot be built until the humidity variation of the foundation soil is balanced and becomes stable.

The following trees are suitable for afforestation:

Evergreen Trees
  Pine, Cypress
Deciduous Trees
  Arbor: Chinaberry, Dawn redwood, Gingko
  Bush: Chinese scholartree, Rose
  Shrub: Cottonrose, Crape Myrtle

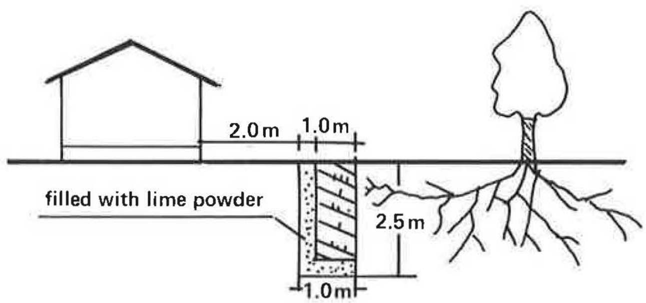

FIGURE 17 Schematic of lime trench separation method.

CONCLUSIONS

The following conclusions can be drawn:

1. Transpiration by water suction of tree roots causes partial shrinking deformation of foundation soil, which causes substantial differential settlements of engineering structures and resulting damage. This is the result of the effect of vegetation on foundation soil.
2. The radius and depth of the sphere in which the vegetation transpiration affects foundation soil is dependent on the species, age, and the growing condition of the roots of the tree. The influence radius of a grown-up tree is 1.4 times the tree height, and its influence depth is 3.5 to 8 m. The degree of deformation will become greater closer to the tree.
3. The effects of vegetation transpiration on dry high void ratio expansive foundation soil mainly occurs in dry and sub-dry climate areas. In the area in which Km > 0.9, e_o < 0.7, or S_1 < 10 percent, the vegetation effects are not significant.

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