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Effect of side ditch water preservation on subsidence characteristics of road pavement under traffic load

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ABSTRACT: The space underneath the road pavement can be an adequate space for rainwater preservation in a sponge city. But after soaked in water, the subgrade soil underlying the water preservation layer will lose much of its strength and cause subsidence problem on the pavement. This study proposes an integrated road base and side ditch system for both water preservation and infiltration. PLAXIS 2D software was used to study the water infiltration behaviour from side ditches with different infiltration boundaries. The spatial distribution and contours of degree of saturation inside the subgrade soil at different time periods were calculated using the flow analysis function of PLAXIS. The mechanical properties of the road base material were selected from the literatures in this study as the first approximation. The traffic load induced deformation in the road base was calculated using the plastic function of PLAXIS. Four types of side ditch configuration were adopted here to study the water infiltration behaviour in the subgrade soil. By correlating the mechanical properties of soil (i.e., cohesion and Young's modulus) to the degree of saturation in subgrade soil, the subsidence characteristics of road pavement under traffic loading can be evaluated. Finally, an integrated road base and side ditch system which can better balance the water infiltration and pavement subsidence is recommended.

1 INTRODUCTION

Due to the global climate change effect, short period and high intensity rainfall event is not unusual recently. Very often, the accumulated rainfall can exceed the capacity of local drainage system and causes flooding problem in urban area. To mitigate high intensity rainfall induced flooding problem, permeable pavement has been proposed to keep some rainwater in the ground and reduce the amount of runoff water directly to the drainage system. Although keeping rainwater under the road pavement can preserve water, moisten the vegetation and cool down local temperature, it can be the nightmare for the road maintenance department unless the soaking and softening problem of subgrade soil can be avoided.

The typical profile of a road base with porous pavement is shown in Figure 1 (PCC 2007). Under this profile design, the water preserved under porous pavement will soften the subgrade soil. To minimize the negative effect of keeping water under the road pavement, an integrated road base and side ditch system is studied here. This system can separate the water preserved under the pavement from the subgrade soil. In the meantime, it can allow water to infiltrate to the ground and moisten the vegetation through the porous side ditch design (Fig. 2).

To study the performance of the integrated road base and side ditch system, PLAXIS 2D software was chosen to analyse the water infiltration behaviour of this system and the road base deformation to the traffic load. Two functions of PLAXIS were used here: flow analysis and deformation analysis. The former focused on water infiltration and distribution within the road base material. The coefficient of hydraulic conductivity of subgrade soil was set to $k=1\times10^{-8}$ m/s. The latter focused on ground deformation induced by traffic load. The soil model adopted for the subgrade soil is set non-porous. The properties of subgrade soil were obtained from the literatures, such as the relationship between mechanical properties and degree of saturation. Then the deformation of the road base material can be calculated.

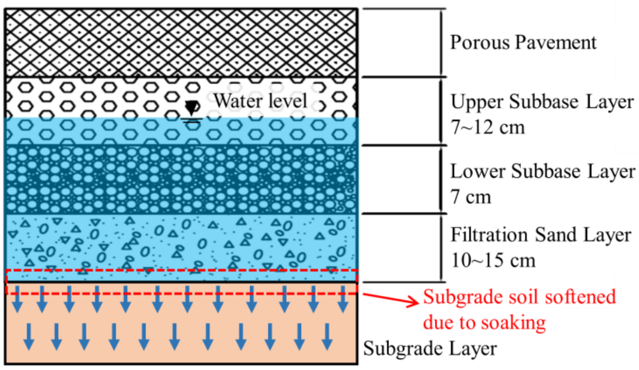

Figure 1. Profile of a road base with porous pavement (PCC 2007)

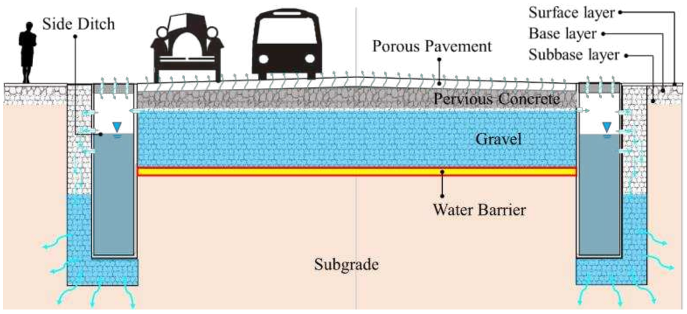

Figure 2. Integrated road base and side ditch system with separated water preservation layer and porous side ditch (Guo 2017).

2 INTEGRATED ROAD BASE AND SIDE DITCH SYSTEM

As shown in Figure 2, the basic concept of this integrated road base and side ditch system is to separate the water preserved under the pavement from the subsoil by using a layer of water barrier between them. The water preservation space can be formed by porous concrete and gravel. Runoff water can flow into the water preservation space through the porous pavement and/or through the tree pit openings on the sidewalk. The water barrier underlying the water preservation layer can be formed by simply spreading a thin layer of colloidal silica grout to the bottom of the preservation layer during road construction (Huang 2016). So, the water kept in the preservation space has no influence on the moisture change of the subgrade soil beneath. Therefore, no soaking induced soil softening will occur. In the meantime, water infiltration to the soil is carried out from the porous side ditch which is surrounded by gravel backfill and allows water perched. Since the area for water infiltration and soil soaking is only around the side ditch and has been kept some distance away from the road pavement, it has little negative effect on the load carrying capacity of the road. But, how to quantify the effect of water infiltration from side ditch on the load bearing capacity of the subgrade soil? It is to be studied in this research using PLAXIS 2D program and the unsaturated soil parameters obtained from the literatures.

In this paper, the water infiltration behaviour from four types of side ditch configuration will be studied namely the U type, UI type, L type and LI type (Fig. 3). Among them, U type and UI type side ditches have gravel backfill placed around the ditch at three sides: the bottom, the road side and the sidewalk side. The U type has the impervious pavement, but no water barrier placed under the water preservation layer; UI type has the porous pavement and the water barrier layer. No water infiltration from the water preservation layer to the subgrade soil is allowed. L type and LI type side ditches have gravel backfill placed only at the bottom and on the sidewalk side. No water is allowed to infiltrate from the road side of the ditch. The L type has the impervious pavement, but no water barrier placed under the water preservation layer; LI type has the porous pavement and the water barrier. No water infiltration from the water preservation layer to the subgrade soil is allowed.

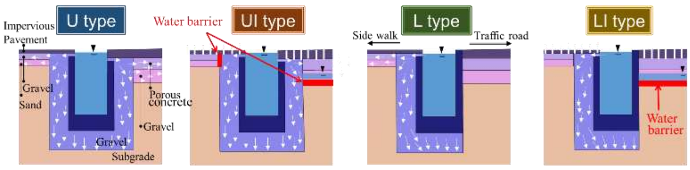

Figure 3. Four types of side ditch configuration studied in this research.

3 NUMERICAL ANALYSIS SETTING

The configuration of side ditch, gravel backfill, pavement and subgrade material used on the numerical study are shown in Figure 4. The depth of the side ditch is 1 m and the backfilled gravel with a thickness of 0.3 m is placed outside of it. Rainwater is allowed to flow to the surrounding gravel layer during heavy rainfall and perch there for infiltration later.

Normally, the groundwater level is located some distance below the road base. So, the subgrade soil material has a low degree of saturation. In other words, the subgrade soil underlying road pavement is under unsaturated condition with low degree of saturation. Without water soaking problem, the subgrade soil may remain unsaturated for a long time and provide a decent load carrying capacity to the traffic load. However, if water is allowed to infiltrate to the subgrade soil through the porous pavement and side ditch, the degree of saturation in the subgrade soil will increase while the soil strength decreases. As a result, extra deformation of subgrade soil may occur under the same traffic load.

Since the mechanical properties of subgrade soil is affected by water infiltration which changes the degree of saturation of subgrade soil, PLAXIS program cannot be used directly to calculate the deformation unless the effect of water infiltration is determined. To find out the mechanical properties change of subgrade soil in the process of water infiltration, several steps need to be proceeded first (Fig. 5).

Mohr-Coulomb model is used in the subgrade layer and gravel layer for the deformation analysis. The drainage condition was set to be drained for the flow analysis with the coefficient of permeability equal to 1×10^{-8} m/s. The SWCC (soil water characteristic curve) used in this study is shown in Figure 6a (Kayadelen et al. 2007). The relationship between coefficient of permeability and degree of saturation is obtained from the following equation provided by Mualem (1976) and shown in Figure 6b.

$$k_r(\theta_w) = \Theta^{0.5}\left[\frac{\int_0^{\theta_w}\frac{\theta_w}{S}}{\int_0^{\theta_S}\frac{\theta_w}{S}}\right]^2$$

where,

θ_r =residual volumetric water content;

θ_w =current volumetric water content;

S =suction;

$\Theta = (\theta_w - \theta_t) / (\theta_s - \theta_r)$;

θ_s =saturation volumetric water content.

The cohesion of soil was obtained through the relationship between SWCC and cohesion as proposed by Kayadelen et al. (2007). The Young's moduli of soil at different degrees of saturation were obtained from the stress-strain curves of soils tested by Kayadelen et al. (2007). The soil parameters used in this study are all correlated to the degree of saturation of soil and listed in Table 2. The deformation analysis was carried out under undrained condition, i.e., the non-porous model in the PLAXIS.

The initial height of perched water in gravel backfill outside the side ditch is set at 1 m. After water infiltrates from the gravel backfill to the subgrade soil, the spatial distribution of degree of saturation at different time periods inside the subgrade soil can be calculated using the flow analysis function of PLAXIS. The contours of degree of saturation in the subgrade soil can be drawn at 10% interval. Using the contours of degree of saturation, the mechanical properties of subgrade soil needed to calculate the traffic load induced pavement subsidence were determined from the published literatures as the first approximation in this study.

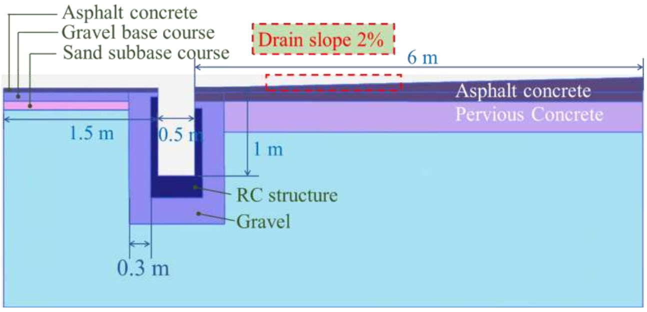

Figure 4. Model configuration for the numerical analysis of U type side ditch.

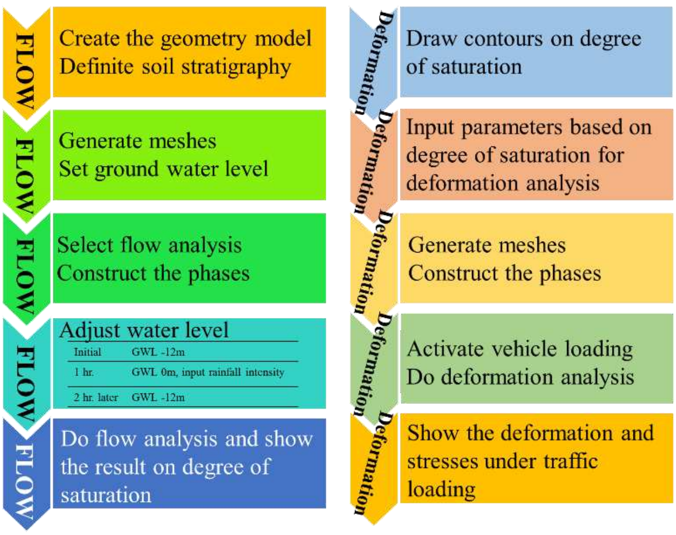

Figure 5. Procedures of the flow and deformation analyses.

Table 1. Properties of subgrade soil underlying the pavement (Kayadelen at al. 2007).

Index property	
Moist unit weight (kN/m^3)	16.45
Dry unit weight (kN/m^3)	14.81
% fine than #200 sieve (%)	95
< 0.001 mm (%)	55
Liquid limit (%)	77
Plastic limit (%)	32
Void ratio	1
Coefficient of permeability (m/s)	k_x*=$1.67*10^{-7}$ k_y=$1*10^{-8}$

(*) Mualem (1976)

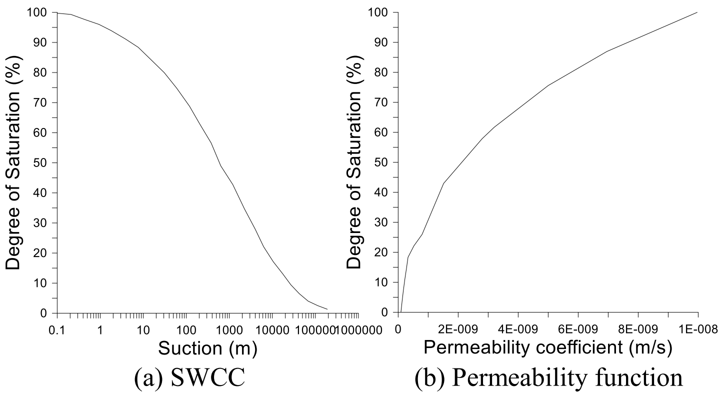

Figure 6. SWCC and Permeability function

Table 2. Mechanical properties of subgrade soil used in this study (Kayadelen at al. 2007 and Mualem 1976).

Identification	Degree of saturation of clay 90%	80%	70%	60%	50%	40%
Material model	Mohr-Coulomb					
Drainage type	Undrained C (non-porous)					
γ_{unsat} (kN/m^3)	16.45					
e_{int}	1					
E (kN/m^2)	6.20×10^3	8.85×10^3	1.26×10^4	1.80×10^4	2.57×10^4	3.67×10^4
ν_u	0.495					
G (kN/m^2)	1.45×10^3					
$E_{oed,u}$ (kN/m^2)	1.47×10^5					
$s_{u,ref}$ (kN/m^2)	22.59	25.48	29.54	34.79	41.21	48.81
k_x (m/s)	1.67×10^{-7}	4.01×10^{-8}	2.55×10^{-8}	2.07×10^{-8}	1.02×10^{-8}	5.07×10^{-9}
k_y (m/s)	1.00×10^{-8}	2.40×10^{-9}	1.53×10^{-9}	1.24×10^{-9}	6.13×10^{-10}	3.04×10^{-10}

4 RESULTS OF NUMERICAL ANALYSES

The results of flow and deformation analyses from this study will be presented and discussed as follows:

4.1 *Results of flow analysis*

Flow analysis was performed first to obtain the degree of saturation and the mechanical properties of subgrade soil needed for the subsequent deformation analysis. The initial degree of saturation at the top of subgrade soil was set at 30% and a linearly increased degree of saturation to the groundwater level was assumed in this study. Based on this assumption, the corresponding groundwater level calculated from PLAXIS was at GL -12m using the soil parameters listed in Table 1. Then a rainfall event with rainfall intensity of 10 mm/hour and a rainfall duration of 1 hour were used. Water level of 1 m height in the backfill gravel around side ditch was adopted. The water perched in the gravel backfill is enough for the subsequent water infiltration to the subgrade soil in the following 10 days.

Figure 7 shows the spatial distribution of different degrees of saturation in the subgrade soil for the 4 types of side ditch after 10 days infiltration. For the U type ditch, water was free to flow into the water preservation layer from the pavement and the side ditch. There was no water barrier placed to prevent the subgrade soil from being soaked by the water. So, the area of large degree of saturation (> 90%) is actually located right under the road pavement. As shown in Figure 6 (a), when the degree of saturation of the subgrade soil is greater than 90%, the matric suction in the soil will decrease to around 22 kPa. In comparison, the UI type side ditch has the water barrier lay down. So, the water infiltration is restricted to the area only around the ditch rather than goes far into the area under the road pavement.

For the L type side ditch, there is no water flowing to the water preservation layer from the pavement or the side ditch. Its water infiltration pattern in the subgrade soil is similar to that of LI type side ditch which has the water barrier placed to separate subgrade soil from the water preservation layer. The water perched in the gravel backfill can only infiltrate to the ground from the bottom and the sidewalk side of the ditch. Although there is some water still manages to infiltrate to the road side of subgrade soil, the area of high degree of saturation is kept some depth away from the pavement. So, its effect on the bearing capacity of road subgrade soil is limited. The areas of degree of saturation > 90% for the 4 types of side ditch after 10 days infiltration, are summarized in Table 3. U type side ditch has the largest area of degree of saturation > 90%.

4.2 *Results of deformation analysis – Two lanes loading*

The spatial distribution of degree of saturation in the subgrade soil after 10 days infiltration from the flow analysis was adopted for the subsequent deformation analysis (use Plastic function of PLAXIS). The contours of different degrees of saturation at 10% interval shown in Figures 8a was obtained from flow analysis of PLAXIS. The model with the spatial distribution of mechanical properties (i.e., Young's modulus E and cohesion c) shown in Figure 8b was determined using the degree of saturation contours shown in Figure 8a and the mechanical properties listed in Table 2.

A two-lane traffic load acting on the pavement is obtained from the vehicle loading regulations set by the Ministry of Transportation, Taiwan. All the vehicle loads used in this study are for the single axle vehicle with a load less than 10 ton per axle.

Only static loading condition is studied here. The tire pressure of passenger car is assumed to be 40 psi (275.8 kPa) and the contact length between tire and road pavement is 35 cm. The tire pressure of truck is assumed to be 80 psi (551.58 kPa) and the tire contact length with the road pavement is 24.7 cm (Huang 2003). The side ditch with no water infiltration function is used as the reference ditch to be compared with the 4 types of side ditch studied here. In the numerical analysis, the initial soil strength of the subgrade soil at the water barrier interface is set to be equal to the strength of soil having 30% degree of saturation.

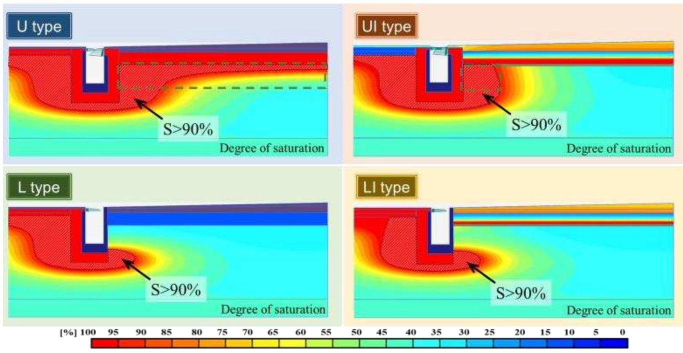

Figure 7. Spatial distribution of degree of saturation for four types of side ditch studied in the flow analysis.

Table 3. Area of degree of saturation larger than 90%

Type of side ditch	U	UI	L	LI
Area of degree of saturation (S) > 90%	4.0 m^2	2.8 m^2	2.1 m^2	1.7 m^2

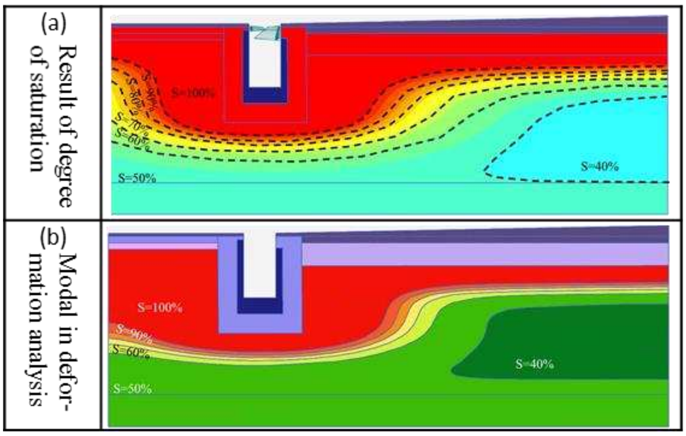

Figure 8. Converting model parameters from flow analysis to deformation analysis.

Figure 9 shows the deformations of subsoil soil when subjected to the truck loading. Not much difference in the deformation patterns between car and truck loadings is found, except truck loading results in slightly larger deformation. This is because, both car and truck loadings are basically within the elastic range of the subgrade soil. In comparison, different types of side ditch configurations can result in obvious difference in deformation patterns of the subgrade soil. After 10 days water infiltration, U type side ditch shows a large area of subgrade soil having a high degree of saturation (> 90%). As a result, the area with larger deformation extends into the area underlying the road pavement. The situation can be mitigated by providing water barrier to prevent water soaking and soil softening from happening, like the UI type side ditch. Since U and UI types of side ditch allow water infiltration toward the road side, so the area with larger deformation is very close to the road pavement and causes larger pavement subsidence (Figures 10 and 11). In comparison, if water is not allowed to infiltrate from the road side of the ditch (L type ditch) and the water preservation layer is underlain by a water barrier (LI type ditch), the mechanical properties of subgrade soil is not much affected by the water infiltration from the side ditch except a weaker area near the bottom of water perched gravel. So, the area with larger deformation is only limited to a depth slightly below the bottom of gravel layer and only causes a minor subsidence on the pavement.

In summary, U type side ditch allows water flow to the water preservation layer and soak the subgrade soil. So, it shows the largest pavement subsidence when subjected to traffic loading. L and LI types side ditches have no water infiltration from the water preservation layer because of impervious pavement (L type) and water barrier (LI type). So, both show a minor pavement subsidence.

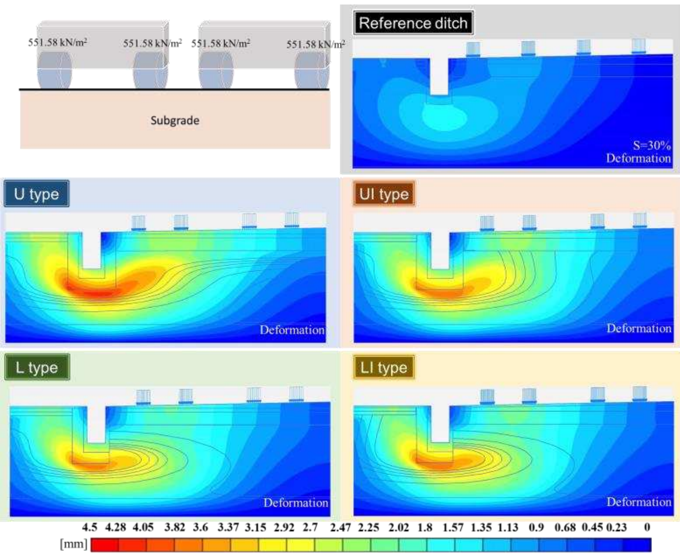

Figure 9. Spatial distribution of deformation in subgrade soil under truck loading (tire pressure 80 psi).

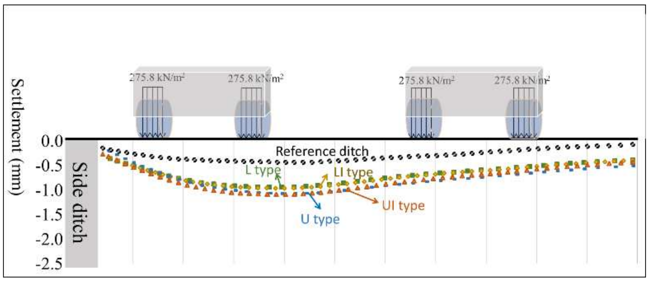

Figure 10. Settlement troughs of car loading (tire pressure 40 psi).

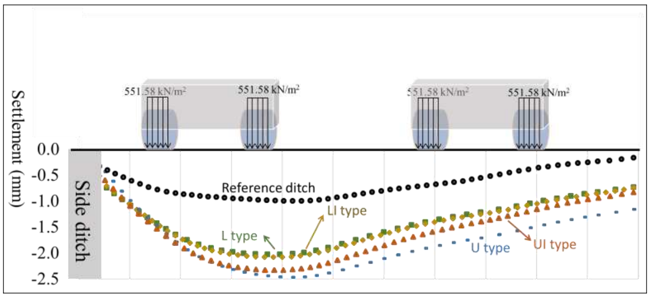

Figure 11. Settlement troughs of car loading (tire pressure 40 psi).

4.3 *Deformation under Cyclic loading and unloading*

To check the effect of cyclic loading and unloading on the pavement subsidence, loading cycle of "load to 40 psi and unload to 0 psi" for 15 times was used. Two-mark points are used to demonstrate the deformation occurs at different locations in subgrade soil (Figure 12, Points 1 and 2). Mark point 1 (Pt 1) locates very close to the top of subgrade. If the water barrier layer is installed, Pt 1 represents the soil in low degree of saturation condition; Mark point 2 (Pt 2) locates around the bottom of the ditch, where the soil is constantly subjected to water infiltration and under high degree of saturation condition. As shown in Figure 12, Pt 2 shows a larger deformation due to its lower Young's modulus (E) value and lower strength (i.e., higher degree of saturation); Pt 1 shows a smaller deformation due to its lower degree of saturation. If a layer of strong soil is provided right under the water preservation layer by keeping the degree of saturation of subgrade soil low, it can be helpful to reduce the pavement subsidence by spreading the load to a larger area and reducing the loading stress to the weaker soil layer below. However, since the loading is within the elastic range of the road pavement and its underlying subgrade soil, cyclic loading did not cause extra subsidence on the pavement from the PLAXIS analysis, which cannot consider the punching effect of the granular particles from the water preservation layer into the water soaked subgrade soil.

The slopes of the stress-deformation curves shown in Figure 12 can be regarded as the coefficient of subgrade reaction at different locations of the subgrade soil. Their values are listed in Table 4.

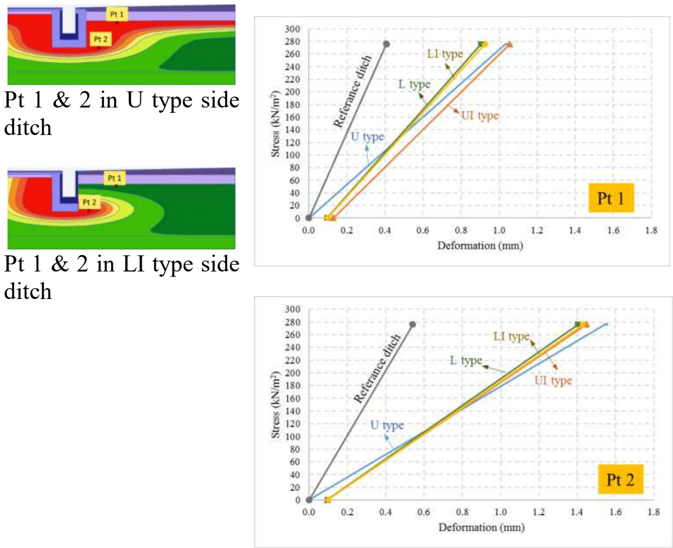

Figure 12. Stress-deformation of mark points 1 and 2 for different side ditch configurations.

Table 4. Coefficient of subgrade reaction in subgrade soil

Coefficient of subgrade reaction (t/m^3)	Reference type	U type	UI type	L type	LI type
Pt 1	687.45	271.69	303.14	340.16	347.73
Pt 2	520.29	182.23	207.72	211.04	215.07

5 CONCLUSIONS

This study is to evaluate the water infiltration effect on the subsidence characteristic of a road pavement. Four different types of side ditch configuration had been used to demonstrate the water infiltration behaviour under different infiltration boundaries. The infiltration induced degree of saturation increase of the subgrade soil will result in extra subsidence of the road pavement. The following conclusions can be drawn from the results of this numerical study:

(1) If water is allowed to infiltrate to subgrade soil underlying the road pavement from the ditch and the water preservation layer as well (U type side ditch). The subgrade soil will be soaked in water. It tends to result in the largest subsidence on the pavement among the four types of side ditch configurations studied here.

(2) LI type side ditch does not allow water infiltrate directly from the ditch to the road side. In addition, a water barrier was placed under the water preservation layer. It has minimized the water infiltration to the subgrade soil. So, the LI type side ditch shows the least effect on the change of degree of saturation in subgrade soil and yields the smallest subsidence on the pavement surface.

(3) Although the effect of water infiltration on the subsidence of road pavement had been studied, the amount of subsidence is significantly underestimated due to the limitation of software used here. The punching effect of granular particles from the water preservation layer into the soaked subgrade soil should be taken into account if the adequate amount of subsidence is to be evaluated.

(4) The proposed integrated road base and side ditch system with a water barrier underlying the water preservation layer can be a win-win alternative for the sponge city. It can provide a large space to preserve water and also moisten the soil for the vegetation. In the meantime, it can also sustain the load carrying capacity of road base (Figure 13). The inlet of water infiltration is from the tree pit. It can help to filter the water to be stored underneath the road pavement.

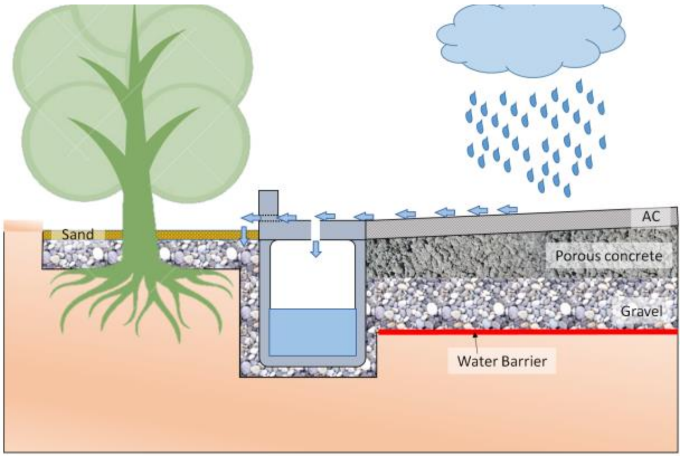

Figure 13. Details of UI type side ditch and gravel backfill.

6 ACKNOWLEDGEMENTS

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