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Study on Calculation Model of Culvert Soil Pressure

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Abstract. Culvert diseases are prevalent in highway engineering. There are many factors involved in the occurrence of the disease, and the problem is complex. However, the design cannot accurately determine the role of the soil pressure on the culvert is the main reason to the disease. Based on the theoretical analysis and field test, this paper studies the characteristics of the stress and deformation of the culvert-soil structure. According to the theory of soil mechanics, the calculation model of vertical soil pressure at the top of culvert is determined, and the formula of vertical soil pressure at the top of culvert is deduced. Through the field test of the vertical soil pressure at the top of culvert of several engineering examples, the calculation formula of this paper is verified, which can provide reference for future practical engineering.

1. Introduction

As the culvert is a hidden project, and there are more than one culverts along the road, which are often overlooked in the daily inspection and maintenance of the highway. The disease is not easy to be found or found when the problem has been serious, and then maintenance and repairing need to spend many man-power and resources[1].The culvert damage related to design, selection, construction, conservation and other aspects. Culvert soil pressure is underestimated, the foundation of geological status which contained culvert, the overall settlement deformation of culvert during the construction and operation and so on will cause damage to the culvert[2].The top of the culvert soil pressure underestimated is the key reason leading to the culvert disease.

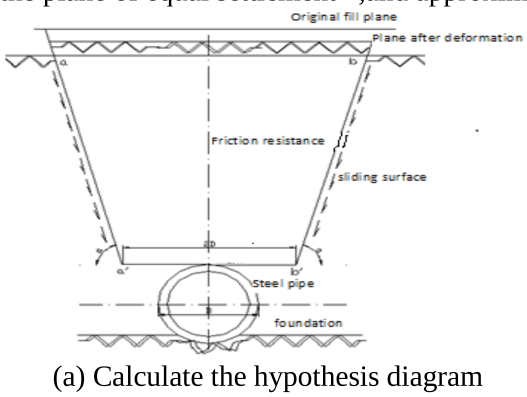
On the calculation of the soil pressure acting at the top of the culvert, Professor Marston first deduced the famous Marston formula in 1913 according to the limit equilibrium condition of the granular material[3].Yemeriyanov used the elastic mechanics differential equation to obtain the calculation formula of culvert soil pressure[4]. Kim and others applied the finite element method, and the Duncan-Chang constitutive model was used to analyze the influence of embedding method, soil type and culvert material properties on the interaction between soil and culverts[5].Zeng Guo-xi considered the influence of soil cohesion on the pressure at the top of the culvert, and modified the Marston formula[6]. Gu An-quan based on the assumption of elastic half-space of rigid foundation and strip foundation settlement calculation, and the Gu Anquan formula for calculating the soil pressure at the top of culvert was derived[7]. Zheng Jun-jie and others considered the actual stress state of the culvert back-filling, combined with the application of finite element analysis method, modified the Gu Anquan formula[8]. After 2000, the technology of finite element has been widely used, and the research of finite element on the calculation of culvert soil pressure has been carried out extensively, Some regular results have been obtained about the joint stress deformation of the "culvert-soil".

The application of linear soil pressure calculation theory in China's current "Highway culvert design rules"[9], without taking into account the joint stress deformation mechanism between the culvert under the high filling embankment and surrounding soil, including the foundation under the culvert, resulting in the vertical soil pressure calculation at the top of the culvert is small. This paper combined with the actual engineering and the study of the whole deformation stress system of "culvert-soil"structure,referenced the results of finite element calculation[10],based on the Marston theory. The calculation model of culvert soil pressure is established and the formula is deduced.

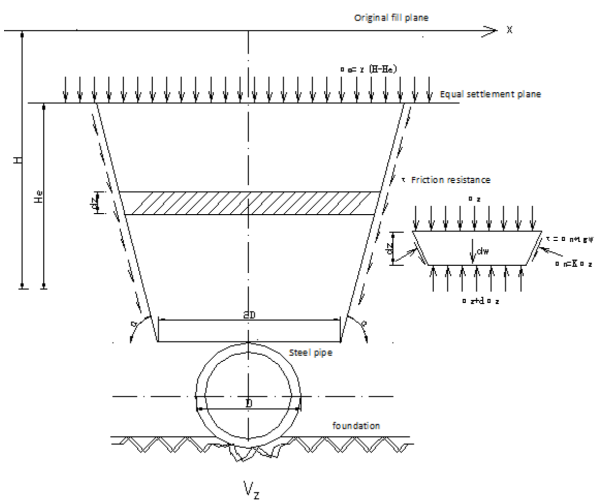
2. Construction of culvert soil pressure calculation modei

Culvert layout in the soil, the culvert stiffness is far greater than the fill and the foundation soil. Under the load of the upper part, the deformation of the culvert will be far less than the side fill and the foundation soil, and then affect and change the settlement deformation of the fill soil and the foundation soil. Among the culvert, fill and the foundation forms a coordination, interrelated, mutual influence unified structure system of deformation and stress, that is, "culvert-soil" structure. Assuming that there is a sliding body and a corresponding sliding surface in the culvert top filling, the width of the bottom of the sliding body is about 2 times the width of the culverts[10], which is different from the width of the single tunnel in Marston's theory. At the same time, the sliding surface no longer use the vertical sliding surface of Marston theory , instead taking a sliding edge sloping to the outside of the culvert. Froming the finite element simulation results, the height of the sliding body[10], which is approximately the same as that of the Marston theory, about 2 times the height of the culvert. Based on this, the mathematical model of vertical soil pressure at the top of culvert is established. Figure 1 shows the mathematical model of the calculation.

The basic assumptions of the calculation model: (1) the deformation of the foundation and the culvert is not considered, that is, assuming that the culvert and the foundation are completely rigid body, the width of culvert is D, the height of culvert is h;(2)sliding surface assumption: the endpoint a',b' along the width of the culvert are diagonally inclined to the height of the fill, arrived at the plane of equal settlement in a and b points, and aa 'and bb' makes up the shearing slip surface during the filling process. The inclination of the sliding surface and horizontal plane is α, according to the principle of soil mechanics, the angle of the shear failure surface in the soil and the large principal stress surface (the principal stress plane is vertical) is $45^o + \varphi/2$, which is shown in Figure 1 is $\alpha = 45^o + \varphi/2$.(3)limit equilibrium assumption: the stress state of the soil on the sliding surfaces besides aa 'and bb' is shown by the limit state of the soil according to the principle of soil mechanics. In this paper, the Mohr-Coulomb yield criterion of soil is used. (4) According to the sink theory of Marston and others, the difference of sedimentation between the soil inside the culvert and the soil outside the culvert is gradually decreased with the increase of the height of the filling. When the filling height reaches a critical value of He, The difference is negligible (the soil above the height of He is considered uniform settlement), the plane corresponding to He is called the plane of equal settlement[3],and approximate He = 2.25h.



(a) Calculate the hypothesis diagram



(b) calculation model diagram

Figure 1 Calculation Mathematical Model

3. Calculation formula derivation

Assuming that the bulk density of the soil is γ, the height of dz of the soil is taken as the isolation body in the sliding roof of the culvert, the width of isolation body is: $x = D + ctg\alpha(H - z)$.

assumption: $\sigma_n = k\sigma_z$;

then: $\tau = c + \sigma_n \tan\varphi = c + ktg\varphi\sigma$;

Regardless of the effect of soil cohesion c,

then: $\tau = \sigma_n \tan\varphi = ktg\varphi\sigma_z$.

In the formula: K is defined as the lateral pressure coefficient of the soil, and the coefficient of active soil pressure of the approximate soil is calculated Ka.

According to the resultant force of the force system in the Z axis is zero(Fz = 0), writing equilibrium formula:

$$(\sigma_z + d\sigma_z)[D + ctga(H - z - dz)] - \tau\frac{dz}{\sin\alpha} \bullet \cos\alpha$$
$$+ \sigma_n \bullet \frac{dz}{\sin\alpha} \bullet \cos\alpha - \sigma_z[D + ctg\alpha(H - z)] -$$
$$\gamma[D + ctg\alpha(H - z)]dz = 0$$

Simplify:

$$\frac{d\sigma_z}{dz} + \frac{\sigma_2(-ktg\varphi + kctg\alpha - ctg\alpha)}{D + ctg\alpha(H - z)} = \gamma \qquad (1)$$

assumption:

$$T = D + ctg\alpha(H - z)$$
$$S = -ktg\varphi + kctg\alpha - ctg\alpha$$

Then the formula (1) is

$$\frac{d\sigma_z}{dT} - \frac{\sigma_Z}{T}Stg\alpha = -\gamma tg\alpha \qquad (2)$$

Get solution:

（3）

$$\sigma_z = C' T^{Stg\alpha} - \frac{\gamma tg\alpha}{1-Stg\alpha} \bullet T$$

In the formula C' is the integral constant.

When H<He, the boundary condition:

$$z = 0, \sigma_z = 0$$

Get solution:

$$C' = \frac{\gamma tg\alpha}{1-Stg\alpha}\left(D + ctg\alpha \bullet H\right)^{1-Stg\alpha}$$

Substituting C 'into formula (3), Get solution:

(4)

$$\sigma_z = \frac{\gamma tg\alpha}{1-Stg\alpha}\left(D + ctg\alpha \bullet H\right)^{1-Stg\alpha} \bullet T^{Stg\alpha} - \frac{\gamma tg\alpha}{1-Stg\alpha} \bullet T$$

When H>He, the boundary condition:

$$z = H_\varepsilon, \sigma_z = \gamma\left(H - H_\varepsilon\right)$$

Get solution:

$$C' = \frac{\gamma\left(H - H\varepsilon\right)\left(1 - Stg\alpha\right) + \gamma tg\alpha\left(D + ctg\alpha \bullet H\varepsilon\right)}{\left(1 - Stg\alpha\right)\left(D + ctg\alpha \bullet H\varepsilon\right)^{Stg\alpha}}$$

Substituting C 'into formula (3), Get solution:

$$\sigma_z = \frac{\gamma\left(H - H\varepsilon\right)\left(1 - Stg\alpha\right) + \gamma tg\alpha\left(D + ctg\alpha \bullet H_\varepsilon\right)}{\left(1 - Stg\alpha\right)\left(D + ctg\alpha \bullet H\right)^{Stg\alpha}}\left[D + ctg\alpha\left(H - z\right)\right]^{Stg\alpha} - \frac{\gamma tg\alpha}{1 - Stg\alpha} \bullet \left[D + ctg\alpha\left(H - z\right)\right] \quad (5)$$

assumption:

$$\begin{aligned} A &= 1 - Stg\alpha = 1 - \left(-Ktg\varphi + Kctg - ctg\alpha\right)tg\alpha \\ &= 1 + Ktg\varphi \bullet tg\alpha - K + 1 = K\left(tg\varphi \bullet tg\alpha - 1\right) + 2 \\ B &= D + ctg\alpha \bullet H_\varepsilon \end{aligned}$$

When z = H: formula (4) is expressed as:

(6)

$$\sigma_z = \frac{\gamma tg\alpha}{A}\left(D + ctg\alpha \bullet H\right)^A \bullet D^{1-A} - \frac{\gamma tg\alpha}{A} \bullet D$$

formula n (5) is expressed as:

$$\begin{aligned} \sigma_z &= \frac{\gamma\left(H - H\varepsilon\right)A + \gamma Btg\alpha}{AB^{1-A}} x^{1-A} - \frac{\gamma tg\alpha}{A} \bullet x \\ &= \frac{\gamma\left(H - H\varepsilon\right)A + \gamma Btg\alpha}{AB^{1-A}} D^{1-A} - \frac{\gamma tg\alpha}{A} \bullet D \end{aligned} \quad (7)$$

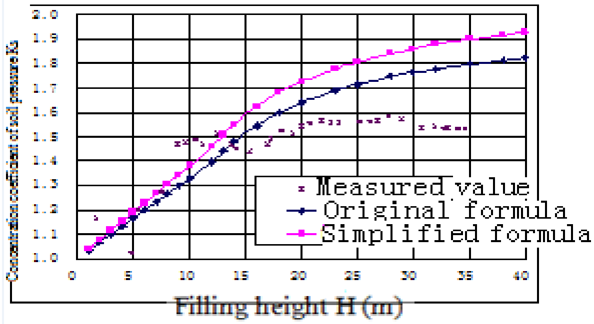
(6) and (7) are the formulas for calculating the vertical soil pressure at the top of the culvert, where the parameter A is determined by the soil lateral pressure coefficient and the internal friction angle of the soil, which reflects the influence of soil parameters. B is determined by the width of the culvert, the height of the plane of equal settlement and the internal friction angle of the soil, which reflects the common influence of culvert and soil.

4. Application of calculation formula

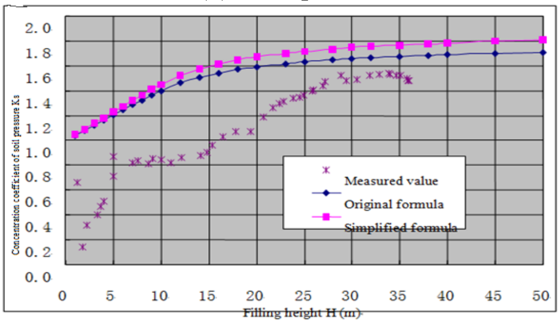
In this paper, the vertical soil pressure at the top of some typical culverts is tested in the field. The height of the filling is 35m or more, which belongs to the high filling culvert. And the vertical soil pressure at the top of the culvert is verified by the formula in this paper. Examples 1 and 2 are respectively k5+536 and k5+905 reinforced concrete arch culvert in a highway. The specific calculation parameters are shown in Table 1 (the soil parameters are taken from the test value of the original soil, K approximate access Ka). The test results are shown in Fig3. The vertical earth pressure at the top of the culvert is represented by the vertical soil pressure concentration factor Ks ,(Ks is the ratio of the actual soil pressure on the top of the culvert and the above filling weight.)

Table 1: Calculation table for soil pressure calculation

Example	Culverts width D (m)	Culvert highlights the ground height H (m)	Filling bulk density g(KN/m³)	pressure coefficient K	Internal friction angle of filling $\varphi(^{\circ})$	$\alpha(^{\circ})$
1	7.6	4.3	18.3	0.20	21^{0}	54^{o}
2	9.0	5.4	18.1	0.21	21^{o}	55^{o}



(a) example 1



(b) example 2

Figure 2 Measured results

In this paper, the formula of calculating the soil pressure concentration coefficient has the regularity with the increase of the height of the filling, which is consistent with the measured results. There is a gap between the measured value and the calculated value, but the gap is not significant. As the filling height continues to increase, the measured Ks value decreases slowly, but the Ks value calculated at this time increases with the increase of H,which is the filling height. In example 1, when the height of the filling is 35 m, the calculated Ks value is 1.8, and the measured value is 1.52;There is a big difference between the two. The calculated Ks in the example 2 are larger than the measured results, and the gap is small in the range of 20m to 30m. Since the culverts of Examples 1 and 2 are buried in a typical valley terrain, the width of the valleys on both sides is about 10.8 m and the slope is about 40 degrees. When the filling reaches a certain height, the terrain factor will have the effect of reducing the load on the vertical soil pressure[11]. The formula in this paper does not consider the influence of this factor on the vertical soil pressure at the top of the culvert. which is the main reasons for the differences between the measured value and the calculated value in the filling height of H is greater than 28m.

5. Conclusions and recommendations

The field test shows that: the overall deformation characteristics of the "culvert-soil" structure leads to a large stress concentration in the vertical soil pressure at the top of the culvert, which is much larger than the weight of filling. The results in this paper show that the vertical soil pressure coefficient is up to 1.8,which must be considered carefully in the actual design and calculation of culvert structure.

The difference between the sliding body in the derivation of the formula and the sliding body in Marston's theory is similar to that of the actual project. According to the results of finite element calculation, the calculation model of soil pressure formula is derived, which is consistent with the actual situation or not, needing to carry out more and more field test results to be verified. The use of the K value of the lateral pressure coefficient in the formula is still to be discussed. In this paper, the validity and accuracy of the formula also need to be tested in more extensive field tests.

In this paper, the test culverts are located in the valley terrain, the influence of the valley terrain on the culvert soil pressure cannot be ignored[12]. In the actual engineering design, the calculation of the vertical soil pressure should be combined with the standard method, the existing measured data, finite element results, and consider the terrain, construction and other factors to determine.

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