Reevaluation of Test Results on Shallow-Burried Structures

Examen Critique de Résultats d'Essais sur des Structures à Profondeur Faible

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SYNOPSIS The contribution of soil arching to the resistance of shallow-buried soil structure interaction systems may become a major factor in the analysis and design of such facilities. This report reevaluates the contribution of soil arching based on the behavior of reinforced concrete box-type structures, and compares the results to experimental and analytical studies, as reported in recent publications.

INTRODUCTION

Recent studies on the resistance of shallow-buried reinforced concrete box-type structures under static and dynamic loading conditions (Flathau et al., 1979; Kiger and Balsara, June and October 1978; Kiger, 1978) suggested that soil arching was responsible for resisting most of the applied load. These results do not conform with basic theories of soil mechanics (Terzaghi, 1943), and more recent studies (Allgood, 1972) which stated that certain depths of soil cover were necessary for developing a high arching capacity of the soil.

The present study was initiated for providing a different approach which may describe the same soil-structure interaction system under consideration. The structural resistance of the structure was derived herein based on the load capacity of reinforced concrete slabs undergoing large deformations. Results obtained from the present study suggest that the structure could be capable of resisting much higher forces than obtained from conventional analytical procedures. Therefore, soil arching may not have been the major mechanism employed by the system for carrying the applied loads. The present results may describe the behavior of shallow-buried soil-structure interaction systems, and also conform with conventional theories on soil arching.

SOIL-STRUCTURE INTERACTION SYSTEM BEHAVIOR

The behavior of the soil-structure interaction system is considered both experimentally based on studies conducted by other investigators (Kiger, 1978; Kiger et al., 1978; Flathau et al., 1979), and analytically based on the behavior of reinforced concrete slabs undergoing large deformations (Krauthammer, 1981).

Experimental Observations

The structure under consideration (Kiger, 1978) was a reinforced concrete box 0.6 m by 0.6 m internal cross section, 2.4 m long, and a wall thickness of 74 mm. The longitudinal reinforcement ratio was 0.01 both in tension and compression, and the shear reinforcement ratio was 0.015. The average uniaxial compressive strength for concrete was 35.9 MPa, the average yield strength of the reinforcement was 514.5 MPa, and the average ultimate strength of the reinforcement was 596.7 MPa. The depth of burial in the soil was 0.3 m, and the resistance function (i.e. the applied pressure on the soil surface as a function of the center deflection of the roof slab), as obtained experimentally (Kiger, 1978), is presented in Fig. 1.

The structural capacity of the roof slab was evaluated both as a conventional beam-column and as a two way slab (Kiger, 1978), and was found to be in the following range: $0.74 \text{ MPa} < w < 1.26 \text{ MPa}$ (Where w is the predicted uniformly distributed load to cause failure of the roof). The applied load on the soil surface was up to about 4.4 MPa, and therefore it was assumed therein that the difference between the applied load and the computed structural capacity was resisted by soil arching. Furthermore, the interface pressure, as measured by gauges installed surface flush in the central region on the structure roof dropped sharply at advanced stages of loading, which was also contributed therein to soil arching.

Assuming a conventional beam-column behavior and employing a modified analytical approach (Krauthammer and Hall, 1979) resulted in obtaining the following structural capacity range: $1.24 \text{ MPa} < w < 1.39 \text{ MPa}$. This capacity, although higher than computed previously based on the conventional analytical approach, was still significantly lower than the 4.4 MPa

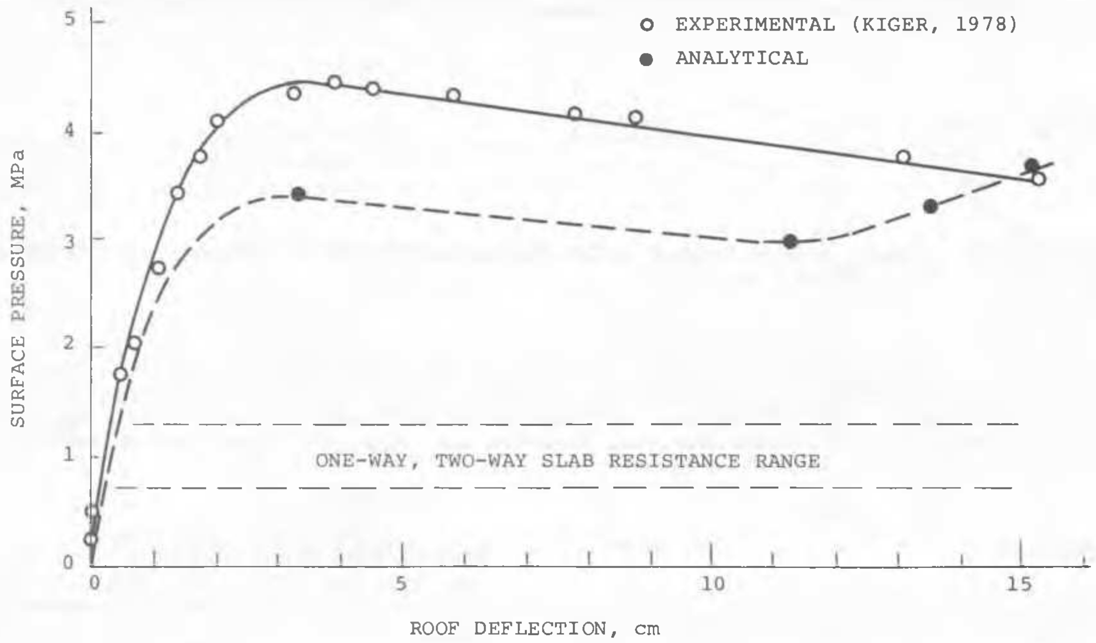

Fig. 1 Resistance Curves for Soil-Structure System

applied pressure. These results demonstrated that the small deformation mechanism employed previously could not simulate the actual behavior of the structure, and therefore a large deformation mechanism had to be chosen for the analysis of the structure under consideration. The deflection of the central region of the roof was up to 152 mm (for a span length of 0.6 m), which also implied that a large deformation mechanism could provide an improved analytical approach for evaluating the structural resistance.

Large Deformation Slab Resistance

The resistance of reinforced concrete slabs, as reported in the literature (Brotchie and Holley, 1971; Hopkins and Park, 1971; Park, March and June, 1964; Tong and Batchelor, 1971; Wood, 1971) can be described as follows. Initially, the slab resistance is provided by the conventional one-way or two-way slab mechanism. However, even at relatively small central deflections the resistance is provided by a compression membrane mechanism, as a result of restraining the outward movement of the slab edges. The peak resistance could be between 2 to 8 times higher than the resistance predicted by the yield line theory (Wood, 1971), and the central deflection associated with the peak resistance is in the range between 0.5d to 0.5t (where d and t are the slab effective and total depths, respectively). After the peak has been reached, a gradual decrease in resistance can be noticed, and eventually the membrane forces in the slab central region are transformed from compression to tension. At that stage the central deflection is in the range of 2d to 2t, and the slab boundaries provide restraint against inward movement of the edges. Extensive tensile cracking is associated with the transition into a tensile membrane, and further deflection of the central zone is associated with an increased resistance which is provided by the steel reinforcement. Failure may be controlled either by shear along the edges (punch-through), or by the fracture of the steel bars in tension.

The slab resistance in the compression membrane mode has been derived previously (Park, June 1964), and modified to include the effects of externally applied thrust forces (Krauthammer, 1981), as follows.

$$
\begin{aligned}
& w\, L_x^2\, (3\, L_y/L_x - 1)/24 = \\
& k_1\, k_3\, f'_c\, t^2\, [(L_y/L_x)\, (0.188 - 0.281\, k_2) + \\
& (0.479 - 0.490\, k_2)] + \\
& 2\, [(L_y/L_x)\, T_x\, (d_{1x} - d_{2x}) + \\
& T_y\, (d_{1y} - d_{2y})] + [(L_y/L_x)\, N_x + N_y] \qquad (1)
\end{aligned}
$$

where:

w	=	Uniformly distributed load on the slab.
L_x, L_y	=	Short and long dimensions of a rectangular slab, respectively.
k_1, k_2, k_3	=	Parameters for describing the compressive stress distribution in concrete, and related to the concrete compressive strength.
f'_c	=	Uniaxial compressive strength of concrete.

t	=	Slab total thickness.
T_x, T_y	=	Tensile forces in steel bars along the x and y directions, respectively.
d_{1x}, d_{1y}	=	Slab effective depth along the x and y directions, respectively.
d_{2x}, d_{2y}	=	Distance from slab compressive plane to the compressive reinforcement along the x and y directions, respectively.
N_x, N_y	=	Thrust in the x and y directions, respectively.

The tensile membrane resistance after the formation of a hinge in the central region of the slab also was derived previously (Park, March, 1964), and was later generalized for demonstrating the influence of the hinge formation (Krauthammer, 1981), as follows.

$$w = 8\ (M_n + T\Delta)/L^2 \qquad (2)$$

where:

w	=	Uniformly distributed load on membrane.
M_n	=	Bending moment in the slab central region.
T	=	Tensile force in reinforcement.
Δ	=	Central deflection.
L	=	Membrane span length.

Analytical Results

The large deformation slab behavior, as discussed previously, was employed herein for describing the resistance curve of the slab under consideration, and the slope of the curve at initial loading stages can be determined from the stiffness of a rectangular slab fixed against rotation, as follows.

$$K = 307\ EI/L^5 \qquad (3)$$

where:

E	=	Modulus of elasticity for concrete.
I	=	Moment of inertia for cross-section.
L	=	Span length of roof slab.

The resistance of the roof slab was computed herein based on the approach which was described earlier (Krauthammer, 1981) by employing Eqs. (1) through (3), and the material properties, as obtained experimentally (Kiger, 1978). The characteristic points of the resistance curve are presented in Table 1, and the curve is illustrated in Fig. 1 where it is compared to the experimental data for the soil-structure interaction system.

TABLE I

Characteristic Points for Slab Resistance Curve

Computed item at stage	Load, in MPa	Deflection, in mm
Ultimate compressive	3.42	33
Transition	3.0	113
Ultimate tensile	3.69	152

DISCUSSION

A conventional analysis of the shallow-buried structure under consideration, as presented in the literature and discussed previously herein, suggested that soil arching may account for about 70% of the measured resistance while the structure may provide the remaining 30%. However, when membrane action enhancement is considered the structural resistance may be significantly higher than the earlier studies indicated. At the peak compression mode the structure may provide up to 78% of the resistance, and soil arching may account only for the remaining 22%. When the tensile membrane is activated the structure may provide an even larger portion of system resistance, as illustrated in Fig. 1.

The sharp decrease of measured interface pressure at the central region of the slab (Kiger, 1978) may be attributed to a combination of the following possibilities:

(i) The interface pressure gauges were mounted surface flush in gauge mounts, and the high compressive stresses in the slab plane caused crushing of the concrete which could damage the gauges, or influence their sensitivity in the direction normal to the slab surface.

(ii) The reactions to the applied load on the slab will not remain vertical as the slab deforms, but will rotate from the vertical direction towards the center of the slab. This gradual rotation may have provided an additional horizontal force component which increased the confinement of the soil located above the central region of the slab. Hence, an increase in the shear capacity of the soil and lower interface pressure reading. However, this possible phenomena should not be confused with the traditional definition of soil arching, and must be confirmed experimentally as well as theoretically.

CONCLUSIONS

The experimental data on shallow-buried structures was reevaluated in the present study, and the following conclusions are drawn.

(i) The structure under consideration can develop a considerably higher resistance than computed in previous studies. The enhanced structural resistance is contributed by membrane action of the roof slab which undergoes large deformations.

(ii) The deflected shape of the roof slab, and the extensive damage associated with the large deformations may cause unreliable measurements of the interface stresses.

(iii) The contribution of soil arching to the overall resistance of the soil-structure system could be in the order of 20% to 30%. Similar contributions of soil arching can be expected based on conventional theories of soil mechanics.

(iv) Further studies may provide additional information on the state of stress in the soil-structure system, and clarify the issue of arching under the given conditions.

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