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Law, K. T.

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by K.T. Law

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Design of a loading platen for testing ice and frozen soil

K. T. LAW

Division of Building Research, Geotechnical Section, National Research Council of Canada, Ottawa, Ont., Canada K1A 0R6

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A critical review of the problems associated with the design of an ideal platen for uniaxial loading tests is presented. A method of design based on an analytical approach is then formulated. The method permits a liberal choice of material for constructing the platen, which consists mainly of a low modulus plug confined in a metallic ring. A finite element approach has been employed to substantiate the proposed method. Practical design aspects are also discussed.

On présente une analyse critique des problèmes associés au dessin d'une plaque de tête idéale pour des essais de chargement uniaxial. Une méthode de calcul basée sur une approche analytique est formulée. La méthode permet un vaste choix de matériaux pour la fabrication de la plaque qui consiste essentiellement en un élément à faible module confiné dans un anneau métallique. Une analyse par éléments finis a été utilisée pour confirmer la méthode proposée. Les aspects pratiques du design sont également discutés.

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Introduction

Law (1977) has made an analysis of the case of uniaxial loading on a cylindrical specimen of frozen soil or ice using a compliant platen, consisting of a low modulus plug confined in a steel ring of diameter slightly larger than that of the specimen (Fig. 1). It was found that for a specimen length-to-diameter ratio equal to 2, satisfactory values of the modulus of compression E, Poisson's ratio ν, and the strength of the material could be obtained if the axial strain was measured for the middle half of the specimen. The analysis, however, did show that significant nonuniform stress and strain still exist at the specimen–platen interface. If higher quality testing is required, if only a short specimen is available, or if the material to be tested is anisotropic in behaviour, a better design of platen is needed.

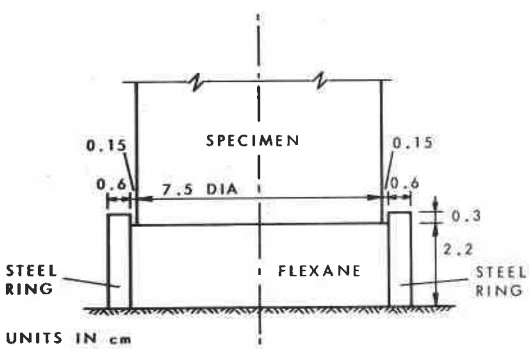

FIG. 1. Sectional view of a typical compliant platen.

Problems in Designing a Proper Platen

The performance of an ideal platen for testing a specimen should satisfy the following requirements.

(1) The lateral deformation should be linear with radius and should be equal to that of the specimen;

(2) The vertical compression should be uniform over the entire interface between the platen and the specimen.

(3) The platen material should be stronger than the specimen.

For a very rigid platen, only requirements (2) and (3) are fulfilled. In this case hardly any lateral deformation occurs during the test. Nonuniform stress and strain are thus introduced. Attempts have been made to free the specimen ends using lubricants or deformable material interposed between the platen and the specimen. This approach does not, however, remove the inherent difficulties. A lubricant introduces problems in controlling the degree of restraint (Hawkes and Mellor 1970), while the deformable material generally violates all the requirements for an ideal platen. The following example illustrates this point.

Consider a specimen of frozen Ottawa sand pressed between two sheets of hard rubber known as flexane (Fig. 2). The mechanical properties of the materials involved are given in Table 1. An analysis based on the finite element method has been carried out. The resulting deformation at the specimen–flexane interface due to a compressive load is shown in Fig. 3.

In Fig. 3a, the computed lateral displacement is compared with that of an ideal platen. At the periphery, the values of the computed and ideal displacements are so close that the purpose of freeing the specimen ends is apparently achieved. Upon further examination, however, the drawback of this platen becomes apparent. The lateral deformation *vs.* radius for the flexane is quite different from that of the ideal case. This difference, in fact, gives rise to a tensile radial stress near the periphery that is more than 25% of the compressive stress.

The calculated vertical deformations, shown in Fig. 3b, provide additional evidence that a deformable material interposed between the specimen and the machine platen does not satisfy requirement (2). Being weaker than the frozen soil, the flexane yields first. Thus, the already nonuniform state of stress and strain is further aggravated.

An alternative approach involves the use of a process known as 'elastic matching'. The basic concept of this approach is to use a platen that would undergo the same radial

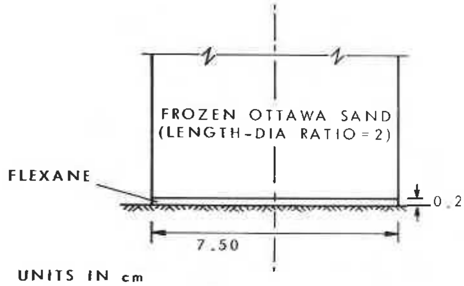

FIG. 2. Cylindrical specimen pressed between deformable sheets.

TABLE 1. Properties of materials used in this study

Material	Modulus of compression (Pa)	Poisson's ratio
Frozen Ottawa sand	1×10^{9}	0.4
Ice	7×10^{9}	0.3
Flexane	5.7×10^{7}	0.49
Steel	2.0×10^{11}	0.27

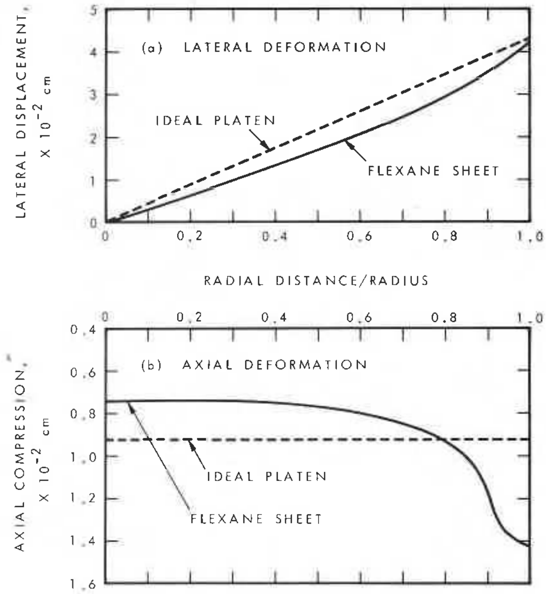

FIG. 3. Deformation at specimen–platen interface.

strain as the specimen. This approach cannot be used, in general, because of the difficulty of finding an appropriate material, particularly for frozen soil whose modulus of elasticity may vary from specimen to specimen and is also dependent on the strain rate.

Another approach employs a dumbbell specimen for testing so that a uniform stress field is induced in the body of the specimen away from the platens. This approach, however, does not remove the possibility of stress concentration near the ends (*e.g.* Paulding 1966). Further, the machining of special specimen shapes is quite an expensive undertaking and may not be feasible for quantity production.

In the past, relatively few attempts have been made to examine critically the stress and strain induced in the platen; yet it is from these attempts that a rational design of platen may emerge. Many versions of designs are based on intuition (*e.g.* Kartashov *et al.* 1970) or on the success of eliminating premature failure (Seldenrath and Gramberg 1958), although the need to look at the design of a platen in a more analytical manner is quite apparent.

Analytical Consideration

Consider a low modulus plug, of diameter $2a$ equal to that of the specimen, confined in an elastic ring (Fig. 4). The condition for

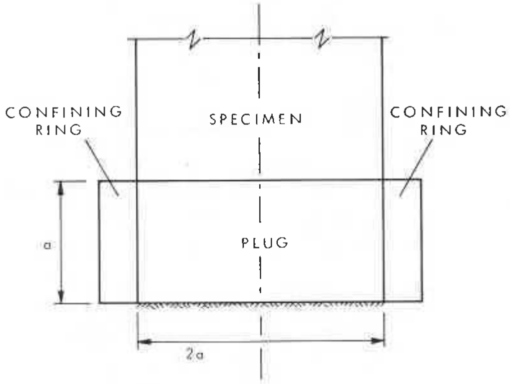

FIG. 4. Schematic view of the proposed platen.

uniform stress and strain at the interface can be written as

$$[1] \qquad \frac{\sigma_z \nu_s}{E_s} = -\frac{\sigma_r}{E_p} + \frac{\nu_p \sigma_\theta}{E_p} + \frac{\nu_p \sigma_z}{E_p}$$

where σ_z, σ_r, σ_θ are respectively the axial, radial, and circumferential stresses in the platen; E_s, E_p are the moduli of compression of specimen and plug respectively; and ν_s, ν_p are Poisson's ratios for the specimen and the plug respectively. It should be noted that, while the axial pressure remains the same in the specimen and the platen, the radial and circumferential stresses change drastically in crossing the interface.

For a length-to-diameter ratio for the plug equal to 1, the radial and circumferential stresses in the plug at the interface are approximately equal (Filon 1902). Equation 1 can then be rewritten as

$$[1a] \qquad \sigma_r = \frac{\sigma_z E_p}{(1 - \nu_p)} \left(\frac{\nu_p}{E_p} - \frac{\nu_s}{E_s} \right)$$

When the ring is absent

$$[2] \qquad \sigma_r = 0$$

and [1a] becomes

$$[3] \qquad \nu_p / E_p = \nu_s / E_s$$

This forms the basis for the 'elastic matching' approach.

To avoid the inherent problem of selecting a specific material for the platen in the 'elastic matching' approach, [1a] should be reexamined. In this equation, the properties of the plug are related to both the properties of the specimen and the values of σ_r generated in the plug. By regulating σ_r one may, therefore, be able to choose a convenient material and yet be able to maintain a state of uniform strain. The problem now becomes how to select a material and design the geometry of the confining ring so that σ_r can be appropriately generated.

Assuming no significant shear stresses are developed between the confining ring and the plug (this can be achieved by suitable lubrication), the radial displacement u_c at the plug–ring interface is given by (Wang 1953)

$$[4] \qquad u_c = \frac{\sigma_r a}{E_c (b^2 - a^2)} [(1 + \nu_c) b^2 + (1 - \nu_c) a^2]$$

where E_c, ν_c are the moduli of compression and Poisson's ratio of the confining ring respectively; and b is the external radius of the ring.

The unrestrained lateral surface deformation of the specimen u_s can be written as

$$[5] \qquad u_s = (\sigma_z / E_s) \nu_s a$$

For perfect matching,

$$[6] \qquad u_s = u_c$$

Substituting [1a], [4], and [5] into [6] and rearranging, one obtains an expression for b. Hence,

$$[7] \qquad b = \sqrt{\frac{1 + C(1 - \nu_c)}{1 - C(1 + \nu_c)}}\, a$$

where

$$[8] \qquad C = \frac{\nu_p}{E_c (1 - \nu_p)} \left(\frac{E_s}{\nu_s} - \frac{E_p}{\nu_p} \right)$$

Equations 7 and 8 also define some physical limits on the choice of material constituting the platen. For a real and meaningful solution of [7], the following expressions have to be satisfied.

$$[9] \qquad 1 - C(1 + \nu_c) > 0$$

$$[10] \qquad \frac{1 + C(1 - \nu_c)}{1 - C(1 + \nu_c)} > 1$$

Substituting [8] into the foregoing expressions gives

$$[9a] \qquad (E_s / \nu_s) > (E_p / \nu_p)$$

and

$$[10a] \qquad \frac{E_c}{1 + \nu_c} > \frac{\nu_p}{1 - \nu_p} \left(\frac{E_s}{\nu_s} - \frac{E_p}{\nu_p} \right)$$

These expressions can be interpreted in the following manner. Any material that is more compressible than the specimen can be employed for making the plug; another material, whose rigidity exceeds a certain limit given by [10a], can be used for constructing the ring. For ice and frozen soil, materials like flexane can be used for the plug and metals like steel or aluminum for the confining ring.

Example

It is necessary to design a platen for testing an ice specimen 15 cm long and 7.5 cm in diameter. The properties of the specimen are given in Table 1.

The designed platen, 3.75 cm thick (equal to the radius of the specimen[1]), consists of a flexane plug confined in a steel ring. The properties of these two materials, also given in Table 1, can be shown to satisfy [9a] and [10a]. Hence, based on these properties, C and b can be evaluated from [8] and [7] to give $C = 0.1115$ and $b = 4.21$ cm, and thus, the basic design of the platen is achieved.

Numerical Verification

The finite element method (Zienkiewicz and Cheung 1967) was used to verify numerically the approach presented in the last section. The numerical modelling is illustrated in Fig. 5. The boundary conditions are:

(1) the mid-plane is prescribed to move downwards in a plane with no lateral constraint;

(2) the base of the platen in contact with the machine is not permitted to move in any direction;

(3) no lateral movement is allowed along the axis; and

(4) a stiffness term S, consistent with the elastic behaviour of the ring, is applied to the nodes at the edge of the plug.

Consideration of slippage at the platen–sample interface is not necessary as it will be shown below that perfect matching is achieved at this interface.

The stiffness term S is defined as the radial force caused by unit displacement at the inner

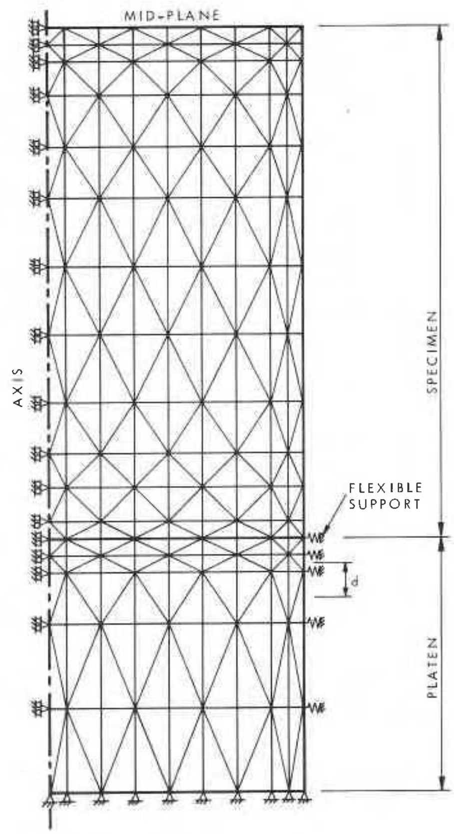

FIG. 5. Finite element model.

surface of the ring. For an axisymmetrical case, S can be derived by integrating σ_r from [4] over the appropriate surface. Hence,

$$[11] \quad S = \int_{z_1}^{z_2}\int_{\theta=0}^{2\pi} \frac{E_c(b^2 - a^2)}{(1 + \nu_c)b^2 + (1 - \nu_c)a^2}\, d\theta\, dz$$

where $z_1 - z_2 = d$, the distance over which the contribution of the pressure is assumed to apply at a node (Fig. 5); and θ = angular distance. Upon simplification and rearranging, [11] can be rewritten as

$$[12] \qquad S = 2\pi C E_c d$$

The example considered in the last section is used here for illustration. The results of computation are shown in Figs 6 and 7, in which the induced deformation and stress in the specimen at the interface are depicted.

The lateral and axial deformation shown in Fig. 6 conforms perfectly to that of an ideal case. The axial, radial, and circumferential

[1]Because the plug deforms uniformly both in the axial and lateral directions at the interface, the length-to-diameter ratio of a single plug is equal to twice the ratio of the thickness to the diameter of the plug.

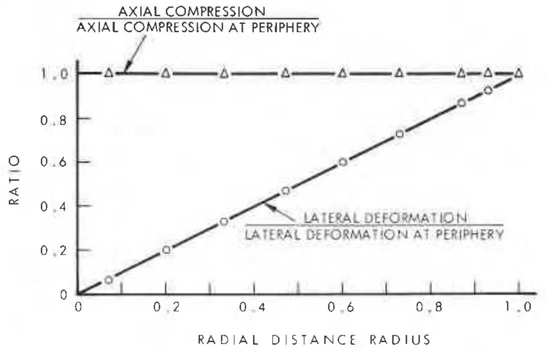

FIG. 6. Computed axial and lateral deformations at specimen–platen interface.

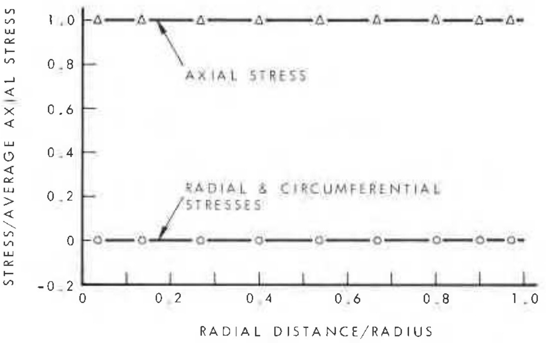

FIG. 7. Computed stresses at specimen–platen interface.

stresses are also remarkably uniform throughout the entire interface (Fig. 7). The plot of radial and vertical deformation with distance from the interface as shown in Fig. 8 indicates that the distribution is quite linear except near the platen base. The numerical analysis, therefore, substantiates the proposed approach.

Discussion

The design procedure presented in this report depends on a knowledge of the material behaviour prior to testing. A problem may arise, therefore, in obtaining such advance knowledge for the proper design of the platen. This problem is, nevertheless, inherent in any approach for the design of platens. To solve this problem tests with steel platen, for example, may be performed on some representative samples. The accuracy of the mechanical properties thus observed would be within about 5% of the actual values (Law 1977). These properties can then be used for the proposed design method.

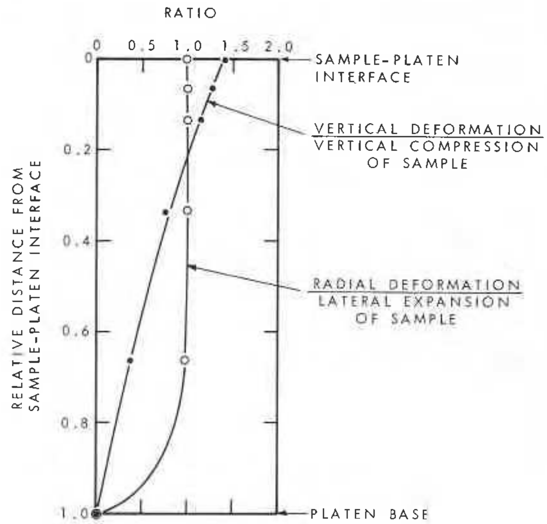

FIG. 8. Vertical and radial deformations within the platen.

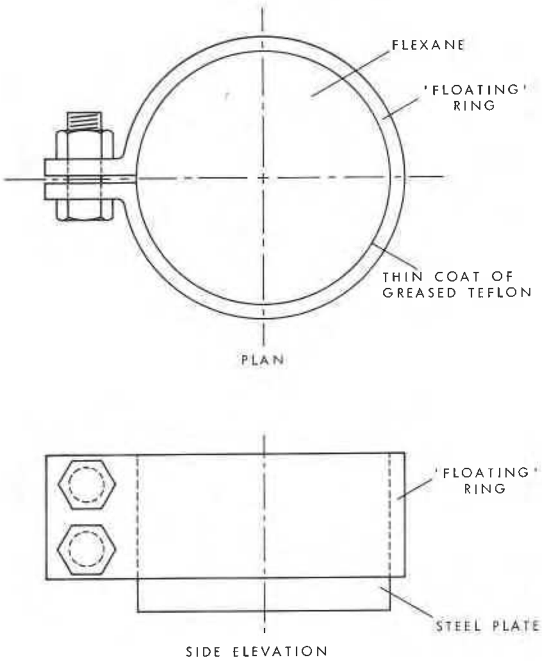

FIG. 9. Proposed platen design.

Friction that may develop at the ring–platen interface can be reduced in two ways. First, lubrication may be introduced by finely machining the inside surface of the ring and then applying a thin permanent coat of Teflon to the surface. Additional lubrication can be obtained by properly greasing the Teflon surface.

Second, to ensure that no axial load is being taken up by the ring it can be 'floated' on the plug. This can be accomplished by gluing the bottom face of the plug to a circular rigid steel plate of the same diameter as the plug (Fig. 9).

A method developed within the Geotechnical Section, Division of Building Research, National Research Council of Canada, can be used to eliminate the problem caused by differential thermal contraction leading to a separation of the ring and the plug. It consists of using a split ring that has a device by which the ring can be tightened as necessary (Fig. 9).

It would be convenient if standard sets of rings of varying thickness were constructed. Once the preliminary properties of the specimen are determined, selection of the proper ring could be made from the available stock.

It should be noted that the proposed design principle would be equally applicable to testing of other stiff materials such as rocks and concrete.

Summary

A rational method of designing platens for uniaxial testing of cylindrical specimens is proposed using the concept of generating proper values of radial and circumferential stresses such that the resulting strain at the specimen–platen interface corresponds to an ideal case, in which the specimen deforms without any end restraining effect. The proposed platen consists mainly of a low-modulus plug confined in a smooth floating ring (Fig. 9). The bottom face of the plug is glued to a rigid metal plate, both the plug and the plate being of the same diameter as the specimen.

This method permits a wide choice of materials that can be used in constructing the platen. The procedure involved has been illustrated by an example which has been further used for verifying the proposed method with a finite element approach.

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