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Miniature Gauges for Soil, Grains and Powders*

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The authors developed miniature gauges for soil, grains and powders mentioned below:

- (a) Pressure cell: measuring the normal stress between grains and wall.
- (b) Friction cell: measuring the tangential stress between grains and wall.
- (c) Internal stress cell: measuring the magnitude and direction of principal stress in grains.
- (d) Gradient cell: measuring the angle of revolution in grains.
- (e) Strain cell: measuring the strain in grains.

In these gauges, (a)~(d) are made up of electrical strain gauges, and (e) is made up of electrical coil.

Then, using these gauges, the experiment of compression of sand in a cylinder was carried out.

In this experiment, the accuracy of gauges was confirmed. And the distributions of resultant stress of wall, and internal stress and strain in sand were revealed.

1. Introduction

When we deal with granular materials such as soil, grain and powder, we want to see the following values:

- (a) Stresses between a wall and granular materials.
- (b) Internal stresses transmitted in the granular materials.
- (c) Deformation in the granular materials.

But we have no suitable gauge to measure these stresses and deformations.

The large pressure gauge which is usually used in prevailing measurement is not adaptable to obtain the stress of small contact area about (a) or (b). And about (c), we have no measuring equipment.

The authors tried to make miniature gauges suitable for measuring granular materials, which resulted in success.

The kinds of miniature gauges tried by the authors are as follows: (Fig. 1)

- (a) Pressure cell: measuring the normal stress between granules and a wall.
- (b) Friction cell: measuring the tangential stress between granules and a wall.
- (c) Internal stress cell: measuring the magnitude and direction of principal stresses in granules.
- (d) Inclination cell: measuring the angle of revolution in granules.

- (e) Strain cell: measuring the strain in granules.

Using these gauges, an experiment of compression of sand in a cylinder was carried out.

2. Pressure cell

2.1 Pressure cell in trial steps

Pressure cell is used to measure the normal stress between granules and a wall.

Some of the pressure cells made in trial steps are shown in Fig. 2.

(a) is the simplest one, but it has the following defects; ① necessity of complex spiral strain gauge, ② scattering of outputs according to the contact points with granules, ③ sensitivity to side pressure, and ④ difficulty in making a diaphragm of fixed thickness.

To correct these defects, (b) is provided with a flange which concentrates the contact pressure, but

Fig. 1 Miniature gauges for granular materials

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it is ① abnormal in output when the point of application is eccentric, ② sensitive to side pressure, ③ small in gain, and ④ difficult to make.

(c) has the construction such that a ball fitted under a diaphragm pushes a detective plate. Thus, the influences of eccentricity of applied pressure and side pressure are avoided, the gain increases, and working becomes easy. But some problems still remain unsolved in assembling and mounting.

2.2 Pressure cell finally obtained

Figure 3 shows the pressure cell finally obtained.

Its construction and function are as follows. A diaphragm bends in the axial direction according to the mean contact pressure. As a displacement of the centre of the diaphragm is transmitted by the ball, the detective plate bends in the axial direction.

Then, the strain gauge fitted on the back of the detective plate stretches. The mean contact pressure is detected as a change of electrical resistance. Any

pressure cell of an arbitrary measuring range can be made only by changing the thickness of the diaphragm.

An example of performance curve calibrated by liquid is shown in Fig. 4. This graph shows that it has excellent linearity and no hysteresis.

The output of the cell depends on the size and position of grains. The cell detects the correct contact pressure only when the grains are sufficiently small. In such a case, it is necessary to know the maximum size of grain.

Fig. 2 Trial pressure cells

Fig. 3 Miniature pressure cell for granular materials

Fig. 4 Performance of pressure cell

Fig. 5 Relation between the point of load and the output of pressure cell

Figure 5 shows the output obtained by putting a concentrated load on several points of different distances from the centre. Figure 6 shows the dependence on the size and position of grain upon the output of pressure cell. This figure means that this pressure cell (diameter 14 mm) can be used for the grain smaller than 2.7 mm in diameter, within the error of 5%.

The temperature drift of the used pressure cell is $2\sim 2.5 \mu\text{st}/^\circ\text{C}$, in the temperature range from 10° to 30°C .

From the facts above mentioned, it is seen that this pressure cell has the following characteristics.

Fig. 6 Relation between a diameter of grain and the output of pressure cell

It is ① very small, ② excellently linear with no hysteresis, ③ made of only one-dimensional strain gauge, ④ simple, ⑤ easily modified for the arbitrary pressure range, and ⑥ it correctly detects contact pressure.

3. Friction cell⁽¹⁾

3.1 Friction cell in trial steps

Friction cell is used to measure the tangential stress between granules and a wall.

Some of the friction cells made in trial steps are shown in Fig. 7.

(a) has the simplest construction. A longitudinal plate bends by the transverse force acting on the friction plate, and its bending stress is detected by a strain gauge. But (a) has the following defects; ① a friction plate inclines by friction force, ② the influence of a normal stress is unavoidable and ③ it is difficult to make a longitudinal plate of desirable thickness.

To correct these defects, the construction of (b) is divided into two parts, one supporting the force and the other detecting the transverse displacement. But (b) has the following defects; ① as an O-ring is used, it is sensitive to pressure and ② the detective plate bends not only by the friction but also by the eccentric pressure.

(c) has a friction plate supported by three balls. The friction plate moves by friction force to the point of balance against the spring force of a piano wire.

Fig. 7 Trial friction cells

A displacement of the friction plate is measured by the bending of detective plate. But (c) has ① poor linearity, ② large hysteresis and ③ high sensitivity to the pressure.

(d) has a friction plate supported by two parallel plates fixed on the bottom. A displacement of the friction plate is transmitted to the detective plate.

The problems of linearity and hysteresis are nearly solved by (d), but the following troubles occurred; ① difficulty of setting the two parallel plates vertical to the friction plate and ② high sensitivity to pressure.

(e) has a saddle-shaped friction plate supported by two parallel plates. The ends of these plates are fixed on the case. A displacement of the friction plate is transmitted to the detective plate. It has good linearity, no hysteresis and no influence of axial pressure, but it is sensitive to pressure on the case. And some problems still remain unsolved in assembling.

3.2 Friction cell finally obtained

Figure 8 shows the friction cell finally obtained.

In this case, granules rub the friction plate, the surface roughness of which is made equal to that of a measured wall. The friction plate is supported by three flexible columns, and moves by the friction force to the point of balance against the spring force of the columns. As a displacement of the friction plate is

Fig. 8 Miniature friction cell for granular materials

transmitted by the ball, the detective plate bends in the radial direction. Then a strain gauge fitted to the back of the detective plate stretches. In this way, friction is detected as a change of electrical resistance.

Any friction cell of an arbitrary measuring range can be made only changing the diameter of flexible column d .

An example of performance curve is shown in Fig. 9. This graph shows that it has excellent linearity, no hysteresis and no influence of pressure.

To summarize, this friction cell is: ① very small, ② excellently linear with no hysteresis and no influence of axial pressure and side pressure, ③ composed of one-dimensional strain gauge, ④ simple and ⑤ easily modified for an arbitrary measuring range.

4. Inclination cell

Inclination cell is used to measure the angle of inclination of a small volume in granules.

Its construction and function are as follows (Fig. 10). A semicircular weight is connected with a case by a thin flexible plate. When this cell inclines according to the motion of granules, the bending moment acting on the flexible plate changes. Then the strain gauge fitted on one side of the flexible plate stretches. In this way, the angle of inclination is detected as a change of electrical resistance.

An example of performance curve is shown in

Fig. 9 Performance of friction cell

Fig. 11. The relation between the angle of inclination and the output is sinusoidal. Therefore, when the angle of inclination is within the range of -30° to $+30^\circ$, the relation between the angle of inclination and the output can be regarded as linear. By the way, it was found that the output of this cell is not influenced by pressure nor the inclination to the transverse direction.

Fig. 10 Miniature inclination cell for granular materials

Fig. 11 Performance of inclination cell

Fig. 12 Trial internal stress cells

5. Internal stress cell

5.1 Internal stress cell in trial steps

Internal stress cell is used to measure the magnitude and the direction of principal stresses around the horizontal axis.

Some of the internal stress cells made in trial steps are shown in Fig. 12.

(a) has the construction such that two pressure cells and two friction cells are attached to an L-form holder. But it was found to have the following defects; ① the friction cell does not measure the friction stress acting between granules and ② the angle of inclination of holder can not be measured.

To correct these defects, (b) has the construction such that three pressure cells and one inclination cell are attached to a triangular holder (made of brass). In this case, however, the trouble is to give granules a considerable disturbance because of its shape.

Then the shape of the holder of (c) is changed to columnar, and the material of which is changed to aluminium to approximate the specific gravity of granules. But it was found that the abnormal concentration of stress occurs because of its rigidity.

5.2 The best internal stress cell obtained

The best internal stress cell obtained is shown in Fig. 13.

Three pressure cells and one inclination cell are attached to a rubber columnar holder. The inclination cell detects the angle of inclination of the internal stress cell itself, and three pressure cells detect the pressures acting in each direction.

From these outputs, the magnitude and direction of the principal stresses are obtained as follows (Fig. 14):

The values σ_α , σ_β , σ_γ , the outputs detected by pressure cells α , β and γ , φ ; the angle of inclination i.e. the angle between pressure cell and the vertical line, are obtained by experiment, and principal stresses and others are calculated by substituting these values into the next equations,

the maximum principal stress;

$$\sigma_1 = \sigma_0 + r$$

the minimum principal stress;

$$\sigma_2 = \sigma_0 - r$$

the angle between maximum principal stress and the vertical line; $\omega = \varphi - \theta$,

where

$$\sigma_0 = \frac{1}{3}(\sigma_\alpha + \sigma_\beta + \sigma_\gamma),$$

$$r = \frac{\sqrt{2}}{3} \sqrt{(\sigma_\alpha - \sigma_\beta)^2 + (\sigma_\beta - \sigma_\gamma)^2 + (\sigma_\gamma - \sigma_\alpha)^2}$$

$$\theta = \begin{cases} \frac{1}{2} \sin^{-1} \frac{1}{\sqrt{3}} r (\sigma_\beta - \sigma_\gamma) & (\sigma_\alpha - \sigma_0 \geq 0) \\ 90^\circ - \frac{1}{2} \sin^{-1} \frac{1}{\sqrt{3}} r (\sigma_\beta - \sigma_\gamma) & (\sigma_\alpha - \sigma_0 < 0) \end{cases}$$

The performances of a single pressure cell and

Fig. 13 Internal stress cell for granular materials

Fig. 14 Calculation of principal stresses from the outputs of internal stress cell

a single inclination cell are described in the previous sections (2.2, 4). To check whether the internal stress cell detects the magnitude and the direction of principal stresses, this cell is buried in dry sand in a cylinder as shown in Fig. 15. The values of σ_α , σ_β , σ_γ and φ are measured in each direction of pressure cell from -90° to $+90^\circ$ at intervals of 30° . From these results, the magnitudes and directions of principal stresses are calculated. The mean value of the maximum principal stresses is 5.3 kg/cm^2 , and the angle of their direction scatters within $\pm 10^\circ$. The real maximum principal stress σ_1 at this point is estimable to be about 2 kg/cm^2 , and its angle of direction to be 0° (c.f. Fig. 24). Therefore, the maximum principal stress indicated by this cell is 2.5 times as large as true value and its direction scatters within $\pm 10^\circ$.

From these facts, the characteristics of the internal stress cell are summarized as follows: It is; ① small, ② detectable the magnitude and the direction of principal stresses around the horizontal axis in granules, ③ simple in construction, ④ easy to make. And moreover ⑤ it indicates 2.5 times as large value as real maximum principal stress, and the direction of itself within an error of $\pm 10^\circ$ when it is used in dry sand.

6. Strain cell

6.1 Strain cell in trial steps

Strain cell is used to measure the strain in one

Fig. 15 Performance of internal stress cell

direction in granules.

Figure 16 shows some of the strain cells made in trial steps.

(a) has the construction of a transformer. As the granules expand or contract, a flanged iron rod moves in a bobbin, and then the mutual inductance between primary and secondary coils changes. Thus the strain in granules is detected as a change of voltage of secondary coil. The volume of case, however, is too large to measure the strain at one point.

(b) is also a kind of transformer in construction, the part of coil is made smaller and a flange is fitted to the case to correct the defect above mentioned. But ① its construction is too complicated, ② the part of coil is still large, ③ granules enter the bobbin, and ④ unlike other cells, it needs a special power source and an amplifier.

6-2 Strain cell in final form

The strain cell in final form is shown in Fig. 17. A flanged iron rod is inserted into a single coil covered by a flanged case. As the granules expand or contract, the rod moves in a bobbin, which causes the change of self-inductance of coil. Therefore, when the strain cell of this type is connected to dynamic strain amplifier of A.C. carrier type as shown in Fig. 18, the strain in granules is detected just in the same way as with other cells of strain gauge type.

An example of performance curve is shown in Fig. 18. The relation between strain and output is nearly linear within the range of strain of 0~20%. Figures 26 and 27 show the experiment to check whether the cell detects the strain in granules correctly. The mean value of strain which is obtained along the centre line in a cylinder is 5.7%. On the other hand, the real mean value of strain calculated from the whole sinking is 8.9%. Therefore, the strain cell indicates 0.64 times as large value as the real strain.

Fig. 16 Trial strain cells

Fig. 17 Strain cell for granular materials

Fig. 18 Connection and performance of strain cell

Fig. 19 Experiment of compression of sand

To summarize the characteristics of this cell, it is ① small, ② able to detect the strain in one direction, ③ linear, (it shows 0.64 times as large value as the real strain in dry sand) and ④ a kind of pick-up of variable inductance type. The strain can be

detected just in the same way as with other cells of strain gauge type by connecting the strain cell with a dynamic strain amplifier of A.C. carrier type. No special electric apparatus is necessary for it.

7. An example of measurement

To confirm the accuracy of developed cells, an experiment of compression of sand in a cylinder is carried out. Numbers of pressure cells and friction cells are set on the walls of cylinder and the punch, and internal stress cells and strain cells are buried in the sand as shown in Fig. 19.

The mean pressure on the surface of punch is

Fig. 20 Distribution of pressure

Fig. 21 Distribution of friction

Fig. 22 Distribution of resultant stress

Fig. 23 Measured values by internal stress cells

changed 0.5, 1.0, 1.5 and 2.0 kg/cm². This experiment reveals the distributions of pressure and friction on the surface of punch, on the wall and on the bottom of cylinder, and also the distributions of principal stress and axial strain in sand.

Figures 20 and 21 show the measured distribution of pressure and friction, respectively.

Figure 22 shows the distribution of resultant stress, which is composed of pressure and friction, in case of the mean pressure 2.0 kg/cm² on the surface of punch.

Fig. 24 Distribution of principal stress

Fig. 25 Transmission of stress

The value of compressing load calculated by integrating the measured distributed pressure on the surface of punch coincides well with the value of applied load. This means that those pressure cells indicate true values.

Moreover in this case, the difference between the axial compressing load on the punch (422 kg) and the axial load supported by the bottom (276 kg), which is calculated by integrating the measured distributed pressure, is 146 kg. This value agrees well with the value calculated by integrating the friction on the wall of cylinder (147 kg). Therefore, it is obvious that these friction cells indicate true values.

Fig. 26 Distribution of strain

Fig. 27 Sinking and rising

The values measured by internal stress cells are shown in Fig. 23, and the distribution of principal stress in sand calculated from the measured data of Fig. 23 are shown in Fig. 24.

Figure 25 shows the transmission of stress in sand.

Figure 26 shows the distribution of axial strain measured by strain cells, and Fig. 27 shows the total amount of sinking and rising.

8. Conclusions

The authors succeeded in developing miniature gauges suitable for measuring granular materials such as soil, grain and powder, which are pressure cell, friction cell, inclination cell, internal stress cell and strain cell.

These gauges are expected to be used in many fields as follows as shown in Fig. 28.

- (1) Rational control of soil compaction and laying of pipe.
- (2) Automation of molding in casting.

- (3) Automation of molding in ceramic and metal ceramic industries.

- (4) Design and automation of vessel for granules.

- (5) Automatic control and research of earth-moving machine.

These gauges also would be useful for actual proof of theory in powder and soil mechanics, and for model experiment in the fields (1)~(5).

9. Acknowledgement

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References

- (1) Dershin, H., *AIAA Jour.*, Vol.5, No.11(1967), p.1934.
- (2) Mogami, T. and Mizuno, H., *The Reports of the Institute of Science and Technology, University of Tokyo*, Vol. 3, No. 11, 12 (1949-11, 12), p. 27.

Discussion

Editorial director:

- (1) How about the difference between two curves in Fig. 6 which indicate the relations between the diameter of grain and the output of pressure cell?
- (2) Is the description about the accuracy of

internal stress cell and strain cell valid in other ranges of stress or strain?

T. SATO (Myogaya Iron Work):

- (3) How about the influence of roughness of the friction plate of the friction cell?

T. IMANISHI (Industrial guidance centre of Aichi Prefecture):

(4) Is it possible to use a pressure cell and a friction cell in measurement of sand containing binder e.g. clay or cornstarch?

G. JIMBO (University of Nagoya):

(5) When the internal stress cell is laid in poured sand, does a gap or a non-uniformity appear under the cell? [about Fig. 12-(b)]

(6) How about the influence of the diameter of objective granules?

Authors' closure

(1) The pressure of granules is essentially the summation of the loads which act on a small unit area and differs from that of continuum or liquid. Therefore, it is necessary to inspect the influence of diameter of granules and contact situations.

When the diameters of granules are uniform, the contact situations will be divided into two typical cases; (a) no grain is located on the centre of the cell, (b) a grain is always located on the centre of the cell. The actual contact situations will be intermediate between (a) and (b). And their outputs will be in the range between curves (a) and (b).

The inspection was not carried out when the diameters of granules were not uniform. But so far as their diameters are smaller than 2.7 mm, the same conclusion will be derived even if they are not uniform.

(2) If the range of them is more than 10 times,

or if these cells are used in wet clay, the description will be invalid. This fact is confirmed by other experiment.

The coefficient of correction depends upon the matching between granules and these cells.

(3) The influence of roughness is considerable, so that a friction cell should be equal to the wall in situation of surface and rigidity.

The influence of the material of the wall is not so serious as that of its roughness (2).

(4) Sometimes, a negative pressure acts in clay.

About a pressure cell: The detective plate is bending even when the pressure is zero. Therefore, even if a negative pressure acts on the pressure plate, the detective plate follows, and the negative pressure is detected correctly.

About a friction cell: The influence of axial pressure is negligibly small. Therefore, even if friction acts on a friction cell with a negative pressure, the friction is measured correctly.

(5) They are considered to appear. But this phenomenon is modified when the cell of Fig. 13 is used.

(6) About the pressure cell, Fig. 6 shows the influence of grains.

About the friction cell, its accuracy is supposed higher than that of pressure cell because of its construction.