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A modified NX-borehole jack with flexible loading platens

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ABSTRACT

The NX borehole jack test is the most widely used method to determine the deformation modulus of rock mass in the field. The common borehole jack, also known as the Goodman jack, has two drawbacks. The first is that the bending of the platens induces extra values in the displacement gauges (LVDTs), which causes the calculated modulus to be smaller than the actual figure. The second drawback is the demand for a perfect rock/platen contact.

A new modified borehole jack has been designed in the present research, which overcomes the drawbacks of the Goodman jack. The new jack incorporates three improvements: (1) LVDTs located in the middle of the jack, (2) flexible platens for full rock/platen contact, (3) a pressure sensor installed at the end of the jack for accurate loading pressure measurement. A detailed theoretical analysis was carried out for the new jack, and experiments on blocks of concrete and sandstone were performed to verify the viability of the conception. The preliminary results suggest that the modified jack has a good theoretical basis, and may lower test requirements for borehole preparation.

The process of borehole jack testing was simulated under plane strain conditions. The results indicate that the rock/platen contact condition of the Goodman jack varies with the modulus of rock and the loading pressure, while the contact state of the modified jack is insensitive to the modulus of the rock. The precisions of the jacks were also analyzed. The results show that the precision of the jack is acceptable when the loading pressure is over 30 MPa; however, when the modulus of rock is estimated to be over 65 GPa, the precisions of the Goodman and modified jack are both quite low.

1. Introduction

The modulus of deformation characterizes the deformability of the rock mass, and is among the most important parameters for geotechnical design (Feng and Jimenez, 2015; Zhang et al., 2013). Many efforts have been made to determine the modulus, both in the laboratory and the field. A comparison of deformation modulus from laboratory and field tests shows that laboratory tests on small samples are inadequate to measure the deformability of rock masses, and field tests must be used, which involve a large volume of rock (Heuze, 1980). There are several methods of field testing, such as plate jacking, plate loading and borehole jack testing, along with some indirect estimates (Agan, 2014; Bieniawski, 1978; Palmström and Singh, 2001).

The borehole jack, commercially available as the Goodman jack, is one of the most widely used in situ test methods for determining the modulus of deformation, as it is simple and convenient. The main drawback of the Goodman jack is that full rock/platen contact is assumed during the test; however, as the present research reveals, the assumption is not easy to satisfy. Some improvements have been proposed for the Goodman jack by alternating the measurement point for displacement (Azzam and Bock, 1987; de la Cruz, 1978). However, because of the complex structure of the devices, the improvements are not widely used.

In the present study, a new modified borehole jack was designed with flexible loading platens, which overcomes the drawbacks of the borehole jack. A detailed theoretical analysis was carried out for the new jack, and experiments on blocks of concrete and sandstone were performed to verify the viability of the conception. For practical purposes, the precisions of the Goodman and modified jack are analyzed, and some suggestions are proposed for the use of borehole jacks.

2. Common NX borehole jack

2.1. Components of the jack and test procedure

The NX borehole jack referred as the Goodman jack in this paper, was developed in the mid-sixties of the twenty centuries (Goodman

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et al., 1968). Today, the Goodman jack remains in common use for directly measuring the in situ elastic modulus of rock. The jack is used in an NX (3 in.) borehole. The main components of the system are the pistons and stiff loading platens. Two models are available: a twelve piston model for use in hard rock, and a three-piston model for determining the consolidation-time properties of soft rock, soil, and stiff clays. The system also includes two LVDT displacement transducers, a hydraulic pump, pressure gauge, hydraulic hose, and electric cable (Yow, 1996).

A detailed description of the test procedure is provided by Yow (1996). First, prepare the borehole carefully to ensure that the diameter of the borehole is within 0.25 mm of 76.2 mm. Then, assemble the equipment and insert it into the borehole to the test location. Finally, raise the hydraulic pressure and push the loading platens toward the borehole wall, and record the gauge pressure and LVDT readings simultaneously.

2.2. Calculations and drawbacks

The elastic modulus is calculated from the formula (Goodman et al., 1968):

$$E_{\mathrm{calc}} = 0.86 \cdot 0.93 \cdot \Delta Q_{\mathrm{h}} \cdot \frac{D}{\Delta \mathrm{D}} \cdot T^{*}(\nu, \beta) \tag{1}$$

where:

0.86	3-dimensional effect factor.
0.93	hydraulic efficiency.
E_{calc}	the calculated modulus of elasticity, MPa.
ΔQ_{h}	incremental change of the applied hydraulic pressure, MPa.
D	borehole diameter, mm.
ΔD	incremental change in displacement, mm.
T^{*}	jack constant, depending on Poisson's ratio and contact angle and given in Table 1.
ν	Poisson's ratio.
β	half contact angle, 45° for the Goodman jack.

In the literature (Goodman et al., 1968; Hustrulid, 1976), different values are suggested for the constant T^{*} in Eq. (1). Heuze and Amadei (1985) explained the discrepancies and proposed a new derivation for the constants (Table 1), which is the latest development in the borehole jack analysis.

Compared with other modulus estimates, such as those obtained using flat jacks, the calculated rock mass modulus, E_{calc}, using Eq. (1) is too low. At first, the possible reasons were thought to be the natural fractures around the hole (Heuze et al., 1971). However, a test in an aluminum block showed that the E_{calc} was less than one third of the known modulus of aluminum (Heyer and McVey, 1974). Numerous attempts have since been made to explain the discrepancy, and two explanations have been proposed (Heuze and Amadei, 1985):

(1) The design of the jack is such that the outermost pistons push the jack plates outward, and this bends the steel plates longitudinally outwards. As the displacement gauges (LVDTs) are located toward the extremities of the jack, any outward plate bending will produce a larger LVDT reading than should actually be read behind the contact platen itself. Therefore, with an artificially higher displacement reading, an artificially low modulus is computed.

(2) Eq. (1) assumes a perfect rock/platen contact over a 90° angle, that is the radius of the hole and that of the jack should be exactly the same. This assumption is quite difficult to satisfy in the field, as discussed in Appendix A of the present paper.

Table 1
T^{*} values with different Poisson's ratio ν, when $\beta = 45°$(after Heuze and Amadei, 1985).

ν	0.1	0.2	0.3	0.4	0.5
T^{*}	1.519	1.474	1.397	1.289	1.151

For the first explanation above, Heuze and Salem (1977) proposed a correction from E_{calc} to E_{true}, based on 3-D finite element analysis for the platen bending, and the correction curve is shown in Fig. 1 for Poisson's ratio ν being 0.33. The correction is insensitive to Poisson's ratio. In practice, the relation in Fig. 1 is used. It should be pointed out that the correction also assumes a perfect rock/platen contact.

In relation to the second explanation mentioned above, Shuri (1981) evaluated the radius mismatch problem, and calculated the progressive increase in contact angle as the pressure was increased for the boreholes being undersize or oversize relative to 3 in (76.2 mm). Based on their research, Heuze and Amadei (1985) provide equations to calculate the minimum hydraulic pressure, which is needed to ensure full contact. For the case of oversize holes, the equation is as follows (Heuze and Amadei, 1985).

$$Q_{\mathrm{hmin}} = \frac{0.1993 \cdot \alpha \cdot 30 \times 10^{6} \cdot E_{\mathrm{true}}}{30 \times 10^{6}(1-\nu^{2}) + 0.91 \cdot E_{\mathrm{true}}} \tag{2}$$

where:

Q_{hmin}	minimum applied hydraulic pressure for full contact condition, psi.
α	hole radius mismatch, mm.
E_{true}	the true elastic modulus of the rock mass, psi.

As the maximum hydraulic line pressure of the device is 10,000 psi (69 MPa), when ν is 0.33 and E_{calc} is 5,000,000 psi (34.5 GPa), the maximum deviation in hole radius beyond which full contact cannot be achieved is only 0.28 mm, according to Eq. (2). This is quite a high demand for borehole preparation in the field.

The two drawbacks mentioned above have limited the practical use of the Goodman jack. The aim of the present study is to overcome these drawbacks.

3. Modified jack with flexible loading platens

3.1. Design of the modified jack

As mentioned above, the common NX borehole jack has two main drawbacks. The first is that the platen deformation adds additional value to the LVDT reading; to overcome this drawback, Li and Zhou (1991) moved the LVDTs to the middle of the jack. The second drawback is that the calculation makes the full-contact assumption; to date,

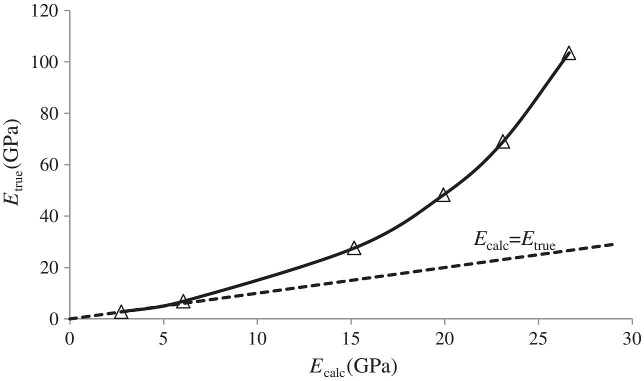

Fig. 1. Correction for platen bending of the borehole jack, assuming full contact. E_{calc} vs E_{true} for Poisson's ratio $\nu = 0.33$ (after Heuze and Amadei, 1985).