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# A Constant Normal Stiffness Direct Shear Device for Static and Cyclic Loading

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**ABSTRACT:** A device has been designed and built to carry out both static and cyclic direct shear tests on specimens of soil and rock and on interfaces of soil or rock and construction materials. The device has the special capability of allowing the shear deformation to proceed under conditions of constant normal stiffness. This is in contrast to the more conventional direct shear devices, which permit shearing under conditions of constant normal stress. It is expected that the constant normal stiffness conditions will be more representative of many in-situ conditions of shear deformation; an important example occurs at the interface of a pile and the formation in which it is placed (particularly those piles that are grouted into the formation). When used with a servo-controlled testing machine the device is capable of applying either static or cyclic shear loading to the test specimens utilizing either load or displacement control. The device is described in this paper, and typical results are presented for static and cyclic loading of a variety of interfaces including some that dilate on shearing and others that collapse as they are sheared.

**KEY WORDS:** piles, shear tests, shear strength, dilation, drilled shafts, laboratories, rock mechanics, rock joints

There are many situations in geotechnical engineering where the mechanical behavior at an interface has a crucial influence on the overall performance of a structure founded in or composed of a soil or rock mass. An obvious example is that of a friction pile or drilled shaft where the ultimate axial load and the behavior at working load are largely functions of the shear transfer capabilities of the shaft-soil or shaft-rock interface. The mechanical behavior of joints is also very important in natural rock masses. Here the strength and stiffness of the interfaces between rock blocks may have an important influence on the mechanical behavior of the overall rock mass. In the case of natural rock joints the presence of water at the interface also may have a significant influence on its mechanical behavior [*1*].

The classical method of testing interface behavior has been in the direct shear apparatus with one of the important aims being to determine the peak shear strength of the interface. Direct shear machines have been described by a number of authors [*1-9*]. Torsional shear devices have also been used to test rock joints, and these allow an examination of the residual strength behavior [*10*]. In both the direct and the torsional shear devices, it is usual for a constant normal load to be applied across the interface while the behavior under steadily increasing shear load or relative shear displacement is observed, that is, the specimens are sheared under conditions of constant normal stress. Tests of this type provide useful strength data for certain types of engineering problems, for example, in studies of slope stability. In the field, blocks of soil or rock may slide upon discontinuities under the action of gravity, and in many cases it is reasonable to assume that the stress acting normal to the shearing plane (because of the self weight of the sliding block), remains constant during shearing.

However, there exists a class of practical problems where the normal stress acting on the interface may not remain constant as sliding occurs. If dilation or contraction were to accompany the shear motion and if soil, rock, or structure on both sides of the interface were constrained in any way, then the normal stress could change during the shearing process. In such cases, it could be unrealistic to model the interface behavior in the laboratory by maintaining a constant normal stress during shearing. More representative behavior would be observed if the laboratory tests were carried out under conditions of constant normal stiffness.

As indicated by Johnston et al. [*11,12*], a particular example in practice where conditions of constant normal stiffness are likely to prevail is at the interface between a pile socketed into rock or a pile section grouted into a soil or rock formation. To at least a first approximation, the stiffness of the surrounding formation is likely to remain constant even if quite large dilations or contractions, and hence significant changes in normal stress, occur at the interface. The dilation or contraction may accompany shear motion at the interface, the latter being brought about by axial displacement of the pile.

After recognizing this important mode of deformation, Johnston and his coworkers devised and built a machine capable of shear testing an interface under conditions of constant normal stiffness (CNS). To date, the apparatus has been used only for static testing involving monotonically increasing shear displacement. Other researchers have also recognized the importance of being able to control independently the shear and normal modes of behavior of a rock interface. A number of new devices have been constructed recently [*13-17*], which have the ability to carry out a CNS test or other tests involving some form of constraint on the dilation of the interface. A review of the testing and modelling of interfaces is contained in a paper by Desai [*18*].

Recently, in an important paper, Leichnitz [*16*] described a device capable of applying either CNS or constant normal stress conditions during testing. He also included two series of test results for dilatant interfaces sheared under both conditions. His results indicate that, although the peak shear stress and the shapes of the

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shear stress versus shear displacement curves depended on which type of normal loading condition was employed, the ratio of shear stress to normal stress at peak and at residual, and the peak rate of dilation during each type of test were functions of only normal stress and shear displacement. He thus provided strong evidence to support the assumption that the shear stress and the dilatancy are functions of only normal stress and shear displacement, independent of the normal stiffness, throughout the entire monotonic shear test. If this result can be validated for many kinds of interface then it may be possible to determine experimentally the incremental stiffness relations for joints and other interfaces in static tests using an apparatus that can independently vary the shear and normal displacements, while at the same time measuring shear and normal stress. Leichnitz's test data were obtained using laboratory prepared interfaces in only one rock type, namely, a sandstone. Testing the validity of his findings for a more general class of interfaces will require the use of testing devices capable of applying a variety of shearing conditions, including CNS and constant normal stress. Furthermore, it is not known what influence the normal loading condition has upon the response of interfaces to cyclically applied shear loading. It is clear that much more experimental data needs to be collected for both static and cyclic shear testing under both constant and variable normal stresses, before these issues can be resolved. Such experimental testing needs to be carried out at both small and large shear displacements.

To date, much of the work on interface testing has been confined to a study of the behavior under monotonically increasing shear displacements. There is now a growing need to test interface specimens in the laboratory under cyclic loading conditions, to observe the effects that repeated applications of shear load have upon the mechanical behavior of the interface. The results of such testing are relevant to the design of piles for offshore structures, particularly where they are grouted into the materials of the seabed.

This paper describes a new constant normal stiffness, direct shear device capable of applying static and cyclic shear loading to a specimen containing one of a variety of possible interfaces. The specimen may contain a specially prepared interface, such as a concrete-rock interface of arbitrary roughness and bonding, it may be formed of two rock blocks from either side of an artificially prepared or a natural discontinuity (for example, a joint or a bedding plane), or it may be an intact specimen of rock or cohesive soil that does not contain a preexisting discontinuity plane. When used in a servo-controlled testing machine, the device is capable of applying either load or displacement controlled static or cyclic shear loading. The cyclic loading may be either one-way or two-way in nature. The device has been used for studying the behavior of concrete-rock interfaces with particular reference to pile sockets and grouted pile sections. Some typical results are included in the paper.

## The Constant Normal Stiffness Condition

As suggested above, if dilation or contraction accompanies shearing at the interface between a pile and the surrounding formation, then to a first approximation the stiffness of the formation with respect to the normal displacement can be regarded as constant. If the pile has a circular cross section then the formation stiffness can be estimated from the solution for the expansion of a long cylindrical cavity in an elastic continuum. It can be shown that the solution for the radial displacement at the cavity boundary is given by

$$u = (p/2G)a \tag{1}$$

where

$u$ = the radial displacement at the cavity wall,
$p$ = the radial normal stress at the cavity wall,
$a$ = the radius of the cavity, and
$G$ = the shear modulus of the formation.

Equation 1 can be rearranged to give the radial stiffness as

$$k = 2G/a \tag{2}$$

The units of $k$ are stress per unit length. Expression 2 is based on the assumption that the soil or rock mass behaves as a linear elastic material, with a constant shear modulus $G$. Of course, in the field situation the response of the formation to an increase in radial pressure within a circular hole (resulting from dilation at the pile interface) may be nonlinear. In the extreme case, radial cracking may occur in brittle materials when the radial pressure reaches sufficiently large values. In calculating an appropriate value of $k$, a suitable choice must be made for the elastic shear modulus of the formation material. If only relatively small dilations are envisaged, then a tangent value of the mass modulus $G$ may be used in Eq 2. If relatively large dilations take place, so that the response of the mass to an increase in radial pressure falls into the nonlinear range, then it will be more prudent to adopt a secant value for $G$. Sophisticated testing devices, using hydraulically controlled rams and a feedback loop to provide normal force-dilation characteristics, could be employed to follow closely any nonlinear variation of $k$ with normal stress. This type of sophistication was not considered in the design of the present apparatus, and thus its further discussion is beyond the scope of this paper.

## Apparatus

The constant normal stiffness direct shear device is illustrated in the photograph in Fig. 1, and a sketch of the major components is given in Fig. 2. The device essentially consists of two collars, which

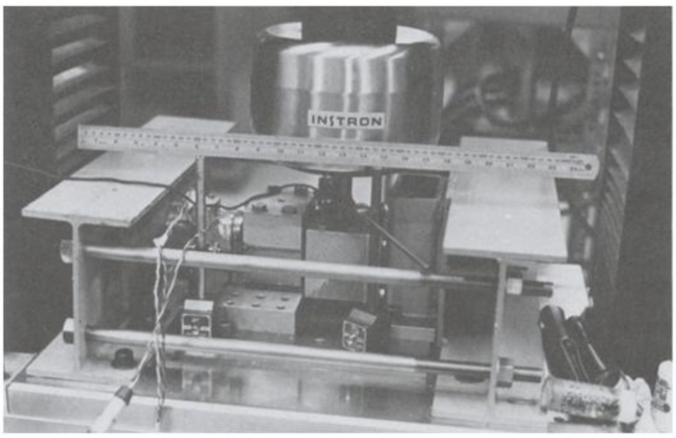


FIG. 1—*Photograph of constant normal stiffness, direct shear device.*

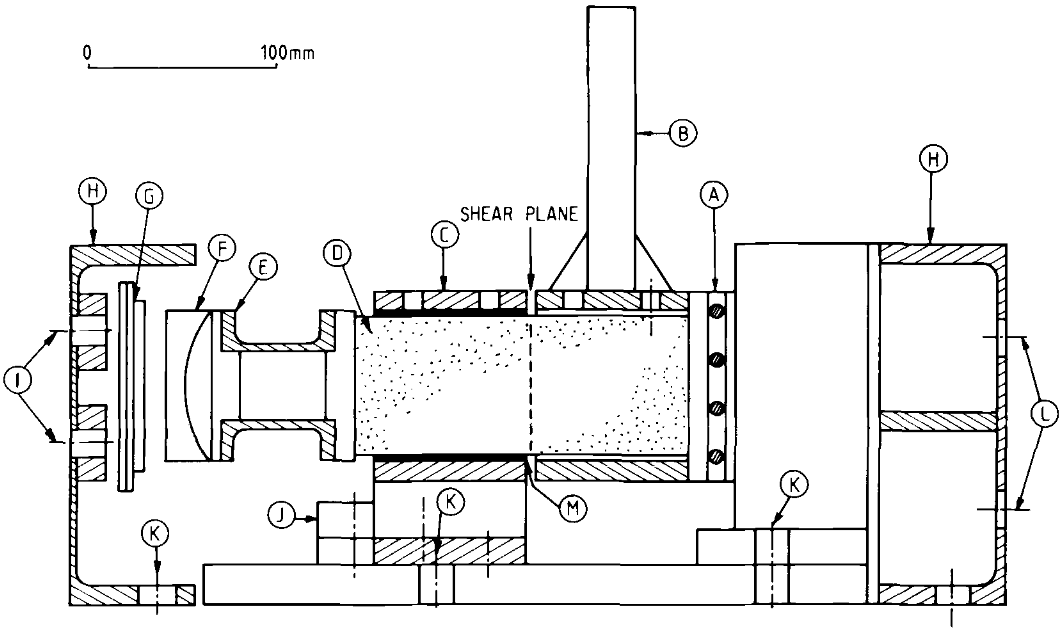


FIG. 2—*Schematic layout of constant normal stiffness shear device.*

grip a core specimen up to 80 mm in diameter. One of the collars (Item B in Fig. 2) is connected directly to the crosshead of a servo-controlled testing machine (an INSTRON Model TT-KM). The crosshead applies the force necessary to cause direct shear on a circular plane between the two collars and normal to the axis of the cylindrical specimen. The second collar (C) is restrained so that movement can occur only in the direction along the axis of the specimen. Movement in this direction will be due to either dilation or contraction of the specimen in the immediate vicinity of the shear plane. Reaction to the normal displacement at the shear plane is achieved through first a load cell (E), then a spherical seat (F), and finally a reaction beam (G). The reaction beam is used to provide the constant normal stiffness condition.

It should be noted that both halves of the specimen are restrained against rotation; the right-hand half is restrained by the roller bearings (A) and the left-hand half by the slider (J). The sketch in Fig. 2 shows that the shear load is applied to the specimen by the collar connected to the testing machine (B). As drawn in the figure, the line of action of the crosshead force is eccentric to the shear plane, and thus there appears to be the potential for bending of the test specimen. An alternative arrangement for the application of the shear load was also manufactured and tested. In this device the straight rod shown as Item B in Fig. 2 was replaced by a cranked rod connected to the crosshead of the testing machine. This rod was cranked so that the line of action of the crosshead force corresponded with the shear plane within the specimen. Extensive testing of control specimens, with both the straight and cranked connecting rods, revealed no significant differences in results. It was thus concluded that if any moment was induced by the eccentric loading arrangement shown in Fig. 2, then it was resisted almost entirely by the rotational restraint (A), and no significant moments were transmitted across the shearing plane.

During testing, the specimen is held by the two collars of the direct shear apparatus. It is possible to grip the specimen directly by these adjustable collars or to cast an undersized specimen into the collars by filling the annular void with cement grout (M). The latter method is preferable if interference of the stress state on the shearing plane by the restraining influence of the collars is to be kept to a minimum during testing. The precise effects of the collar restraints on the shearing plane stresses are unknown at this stage.

The magnitudes of the applied shear force, the normal force, and both the shear and normal displacements are monitored throughout each test. The shear force is measured by a load cell that is mounted on the crosshead of the testing machine. This full bridge, strain gaged load cell has a maximum capacity of 250 kN. The load cell system has a built-in load signal amplifier to allow for the selection of different load ranges. The shear displacement is measured by using a strain gage extensometer, which has mounting points on both collars of the shearing device, adjacent to either side of the shearing surface. The operation of the extensometer is based on four foil-type strain gages bonded to a metallic element in the form of a Wheatstone bridge circuit. The extensometer is calibrated using a high magnification micrometer that can be read to 0.0005 mm. The selection of extensometer depends on the accuracy and range required; typical ranges available are between 0.05 to 0.5 mm and 2.5 to 25 mm. The selection of a suitable full-scale deflection can be achieved by setting the appropriate gain on the strain signal amplifier unit.

The normal force is measured using a load cell (E) with a capacity of 100 kN. It is manufactured from a high grade steel and has a total of eight strain gages glued to the walls of a thin-walled cylinder at 90° intervals around the circumference. The strain gages are connected to form a full bridge and have been waterproofed and protected against minor accidents. A linear variable differential transformer (LVDT) is used to monitor the changes in normal displacement during testing. A high magnification micrometer is used to calibrate the LVDT. In an early version of the device this LVDT was mounted at the left-hand end of the specimen. When in this position, it not only measured normal displacements of the interface, but it also measured any axial deformations of the host rock (D). The latter are not usually significant unless the stiffness of the host material is very low. In the most recent version of the device this potential source of error has been removed by mounting the LVDT on the collars on either side of the shearing plane.

As mentioned above, the constant normal stiffness is achieved by means of a simply supported beam (G). (A similar effect could have been achieved with a linear spring.) The normal load cell bears directly on one side of the spherical seat (F) and the other side of the seat bears directly on the center of the simply supported beam (G). The value of normal stiffness can be adjusted by varying the thickness of the beam or by adjusting the distance between its supports.

The voltage outputs of the monitoring devices (load cells, extensometer, and LVDT) are suitably amplified and then fed into an analog-digital converter and stored in the memory and on floppy disks of a microcomputer system for later processing. The signals are also sent directly to $X$-$Y$-$Y$ and chart recorders. The latter devices form an essential back-up recording system, as well as a convenient means of monitoring the results during testing.

The use of a servo-controlled testing machine means that the specimen can be forced to follow a variety of shear load and displacement controlled test paths, including cyclic paths. Figure 3 shows schematically the control system that is used. The command signal from a function generator and the feedback signal from the monitoring device (shear load cell or extensometer) are subtracted and the "error" signal is used to drive the hydraulic motor to close the control loop. Stability of the control loop is dependent on the stiffness of the specimen and the changes that occur during cyclic loading tests. Tests with an amplitude of cyclic displacement of up to 1 mm and a frequency of 0.08 Hz have been carried out successfully. Static shear testing to a maximum shear displacement of about 25 mm is possible at rates of up to 200 mm/min.

### Specimen Preparation

Specimen preparation techniques vary depending on the size and strength of the specimen. In the case of rock core, oversized specimens are usually trimmed to a diameter of approximately 76 mm with a diamond coring bit, so that the specimen can fit comfortably into the two collars of the direct shear device. Undersized cores are grouted into the collars using a suitable grout material. The specimens are usually cut to a length of about 170 mm with a diamond saw, however, shorter specimens can be mounted in the collars with the use of metallic spacers. After mounting in the collars, appropriate normal load is then applied to the specimen and the collars tightened around it. The position of the crosshead of the testing machine is carefully adjusted to eliminate any small shear loads induced because of misalignment.

Later in this paper a number of tests on sandstone-concrete interfaces are described. The triangular asperities of these rough specimens were made by filing the sandstone with a carborundum block until the interface conformed with the contours of a steel template guide. The cross section of the asperities used in these tests was an isosceles triangle with a height of 2.5 mm and a base width of 9.5 mm. Each specimen had a total of eight parallel asperity ridges across the shear plane, perpendicular to the direction of shearing. The other half of these test specimens was formed by casting concrete onto the roughened sandstone interface.

Direct shear tests on specimens of circular section are not as common as tests on square or rectangular sections. A particular criticism of the test on circular specimens concerns the nonuniform loss of contact that occurs during shearing and the relatively complicated form of the area correction that should be applied in these tests. If desired, these objections could be overcome in the present device by casting specimens of square cross section into the circular collars of the shear device. This would of course reduce the available contact area below the area of the circular collar (maximum diameter of 80 mm). Furthermore, circular specimens are attractive because of the relative ease of preparation with a coring drill. The results presented later in this paper were all obtained for specimens with a circular shear plane.

### Test Variables

During testing, the number of variables that may be controlled depends on whether the loading is static or cyclic and whether the shearing involves load or displacement control. The variables over which control can be exercised are

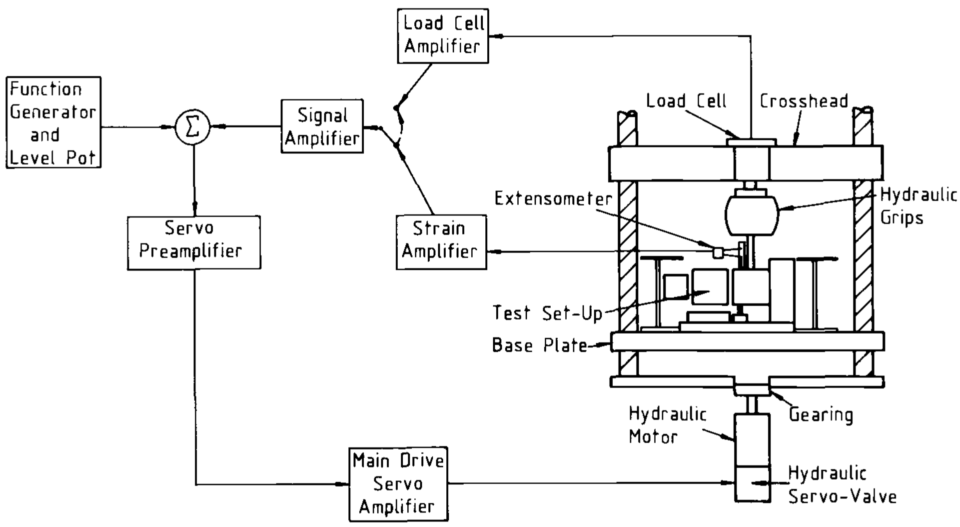


FIG. 3—*Layout of test control.*

(1) the initial normal load,
(2) the constant normal stiffness,
(3) the rate of shearing in static tests, and
(4) the load or displacement amplitude and the frequency during cyclic tests.

For the application to piles, the initial normal stress may be calculated from the head of the column of grout or concrete or the expected grout pressure during construction of the sockets or inserts. The spring stiffness is calculated from Eq 2 with the appropriate value of the elastic parameter $G$ for the soil or rock formation and the appropriate pile radius $a$. If behavior under cyclic loading is of interest, as would be the case for piles in an offshore environment, then the effect of wave loading superimposed on dead loading can be used to estimate suitable cyclic shear stress or displacement amplitudes. In this case the rate of cyclic loading may be determined from the wave period.

## Typical Results

Some of the uses of the machine are illustrated by presenting some typical results. Both static and cyclic shear tests are considered, and the results are presented for materials that dilate upon shearing and others that undergo volumetric collapse as they are sheared.

### Static Tests

Some results of static direct shear tests are presented in Figs. 4 through 6 for different specimens, labelled as (a) and (b) on the figures. Specimen a contained a specially prepared rough interface of sandstone and concrete. The sandstone contained predominantly quartz grains set in a matrix of silica and clay minerals. The sandstone portion was formed from a piece of core cut so that it had triangular asperities at the interface, and onto this was cast a cylindrical piece of concrete, which formed the other half of the specimen. Geometric details of these asperities have been described previously. Specimen b contained no specially prepared interface but consisted of an intact core specimen of naturally occurring carbonate sandstone (calcarenite). The porous calcarenite had a high carbonate content (greater than 90%) and consisted of sand sized particles and shell fragments that were weakly cemented together by other carbonate material.

The initial normal stress applied to each specimen and the initial normal stiffness used in each test are listed in Table 1. The values

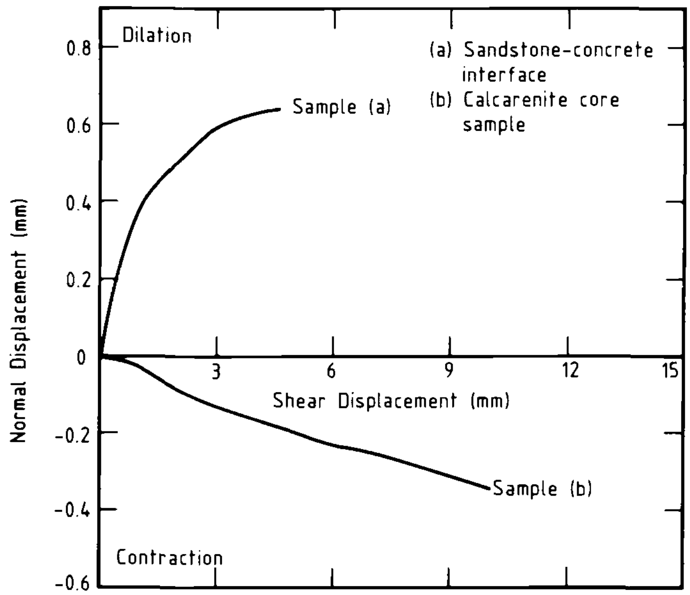


FIG. 5—*Normal displacement versus shear displacement for static tests.*

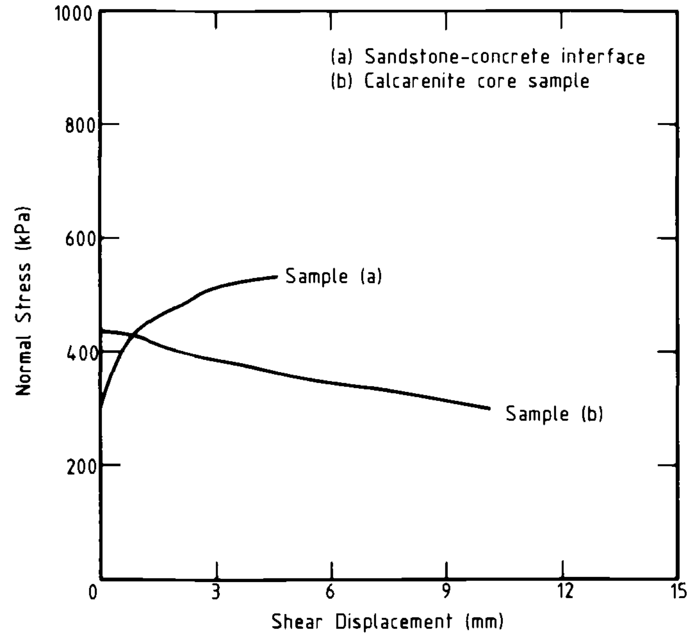


FIG. 6—*Normal stress versus shear displacement for static tests.*

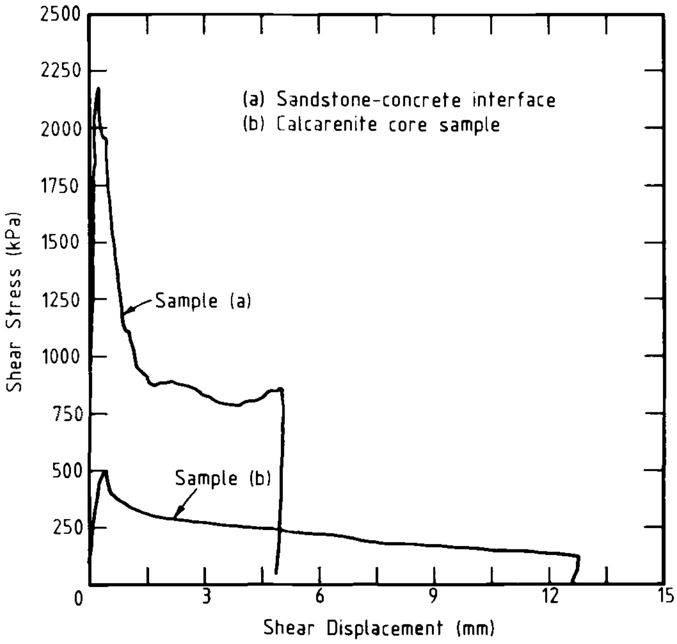


FIG. 4—*Shear stress versus shear displacement for static tests.*

TABLE 1—*Test details, Specimens a to d.*

| Specimen | Type | Initial Normal Stress, kPa | Normal Stiffness, kPa/mm |
|---|---|---|---|
| a | sandstone-concrete | 311 | 340 |
| b | calcarenite | 433 | 400 |
| c | sandstone-concrete | 247 | 500 |
| d | calcarenite | 518 | 380 |

of normal stiffness were calculated before shear testing from the results of a calibration test on the normal load cell-reaction beam system, in which forces were applied to the system using a hydraulic jack. The normal stiffness was obtained by plotting the force measured by the load cell against the deflection of the beam. The slope of this line was then divided by the area of the shear plane of the specimen to give the normal stiffness. The stiffness of the normal reaction system can also be checked continuously during testing by monitoring the normal load and the displacement of the reaction beam.

Figure 4 shows a plot of average shear stress versus the monotonically increasing shear displacement. Both specimens exhibit a pronounced peak shear strength followed by a reduction in strength as the deformation is continued. Before the peak shear stress is reached, the response of each specimen is almost linear on the plot of shear stress versus shear displacement. For Specimen a the peak shear strength was measured as 2200 kPa and beyond the peak the shear stress at first decreased rapidly with increasing shear displacement but eventually levelled out to an approximately constant value of 790 kPa. The peak shear strength of Specimen b was measured at 510 kPa, and beyond the peak the stress also decreased rapidly, but unlike Specimen a the decline in strength continued while the shear displacement increased. The test on this specimen was terminated at a displacement of about 12.5 mm.

Not only is the relationship between shear stress and shear displacement of interest in a direct shear test, the coupling between the shear behavior and the normal displacement and normal stress is also of some interest. Figure 5 shows the relationship between the normal displacement and shear displacement, and Fig. 6 shows plots of normal stress versus shear displacement for Specimens a and b. These plots clearly indicate the marked difference in shearing behavior of these two types of interface. While Fig. 4 plainly shows that Specimen a is stronger than Specimen b, Figs. 5 and 6 indicate that the mechanism of shear displacement and shear failure are indeed different for the two specimens. The shearing of Specimen a is accompanied by a significant amount of dilation at the interface, and this dilation is observed even before the peak shear strength is reached. Since dilation occurs under conditions of constant normal stiffness, this results in a large increase in normal stress acting across the shear surface. An increase in normal stress will contribute to an increase in the frictional component of the peak and post-peak shear strength. Because some dilation and an increase in normal stress had occurred before the peak response was observed, it can be concluded that for this specimen the normal stiffness (through its effect on normal stress) was important in determining that peak strength. In contrast to this behavior, Specimen b exhibits contraction at the interface, and in this case a reduction in normal stress occurs as the shearing proceeds. It is worth noting that for this specimen the contraction was almost negligible until after the peak response, but once it had begun it then contributed, through a loss of normal stress, to a rapid decrease in shear strength. A further implication is that the normal stiffness had little effect on the peak shear strength because contraction at the interface and the consequent reduction in normal stress was not significant until after the peak response.

The stress paths followed by each specimen during static testing have been plotted on Fig. 7. In both cases the paths rise steeply; they then pass through a peak in the applied shear stress and subsequently follow a descending path until the completion of each test. The major difference between the two paths is the direction of travel relative to the normal stress axis: the path for the dilatant sandstone-concrete interface moves to the right, indicating an overall increase in normal stress, while the path for the calcarenite specimen moves to the left, indicating a reduction in normal stress with shearing.

## Cyclic Tests

The behavior of two different types of interface under conditions of cyclic shear loading is now considered. As before, results are presented for the specially prepared sandstone-concrete interface and for a core specimen of calcarenite. These are designated as Specimens c and d, respectively, and they are similar to the corresponding Specimens a and b discussed above. The initial normal stress and normal stiffness conditions for each cyclic test are set out in Table 1.

## Sandstone-Concrete Interface

It has been demonstrated above that a sandstone-concrete interface will tend to dilate under monotonically increasing shear displacement and that under conditions of constant normal stiffness this dilation will result in an increased frictional component of the shear strength. It is also of some interest to examine the behavior of such an interface when subjected to a cyclically varying shear load-

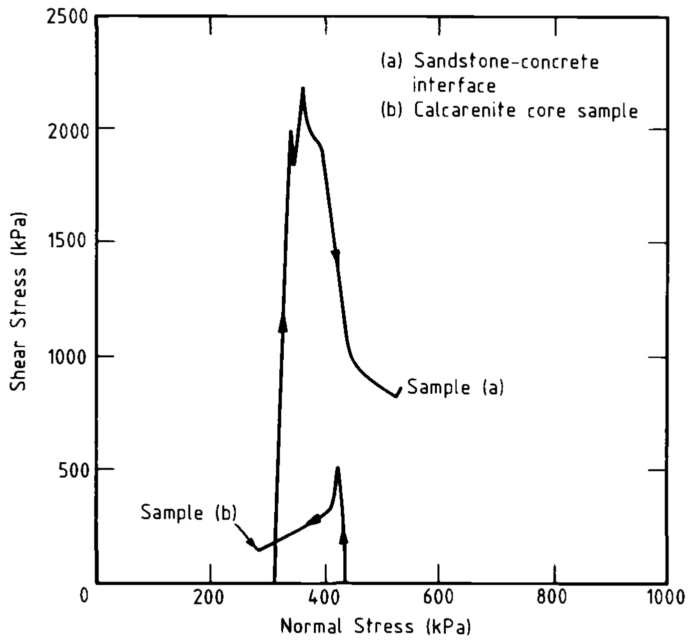


FIG. 7—*Stress paths during static tests.*

ing. In particular it is of interest to see if the tendency to dilate is affected by cyclic loading and to learn whether any degradation in shear response occurs during and as a result of the repeated loading.

Figures 8 to 12 present the results of a cyclic shear test on a sandstone-concrete interface (Specimen c). This specimen was initially

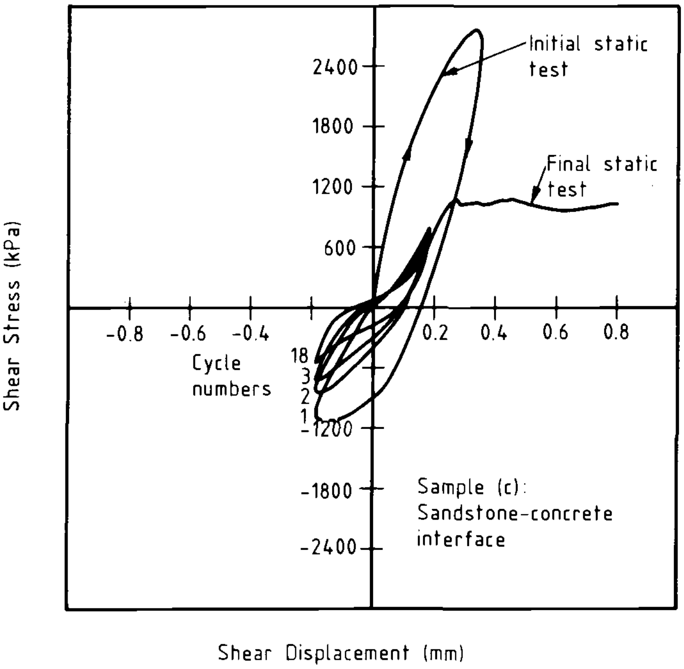


FIG. 8—*Shear stress versus shear displacement for static and cyclic tests on Specimen c.*

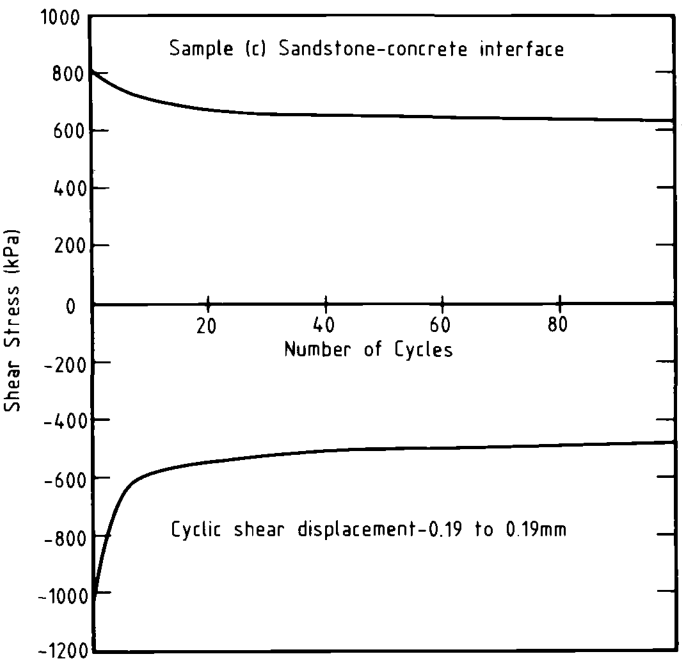


FIG. 9—*Envelopes of maximum shear stress versus number of cycles for cyclic test on Specimen c.*

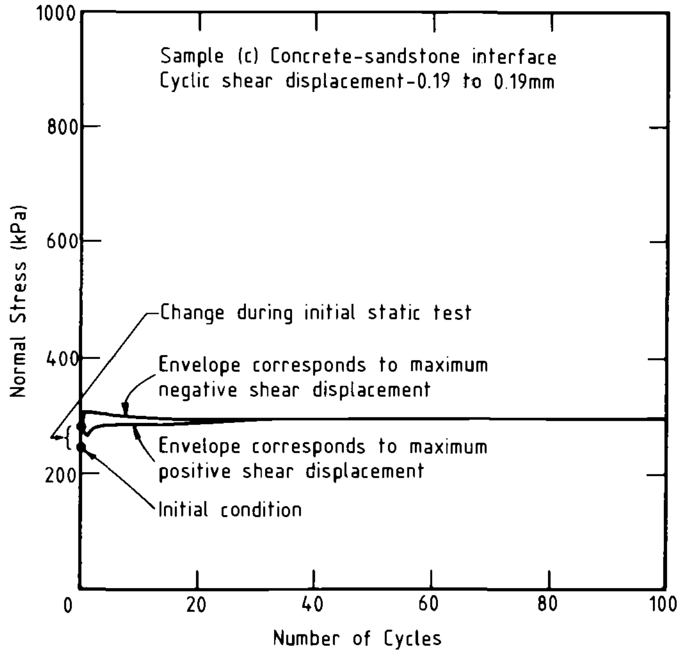


FIG. 10—*Normal stress versus number of cycles for cyclic test on Specimen c.*

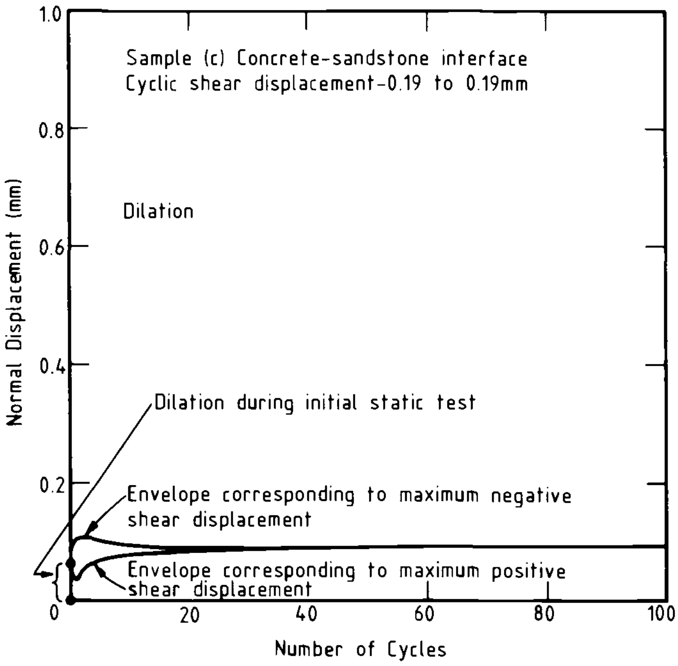


FIG. 11—*Normal displacement versus number of cycles for cyclic test on Specimen c.*

loaded statically to just beyond its peak shear response (at approximately 0.35 mm of shear displacement) and was then unloaded to zero shear displacement. It was subsequently subjected to repeated two-way, displacement controlled shearing with an amplitude of 0.19 mm. This cyclic loading was carried out with a frequency of 0.0033 Hz. This represents a low rate of shearing (approximately

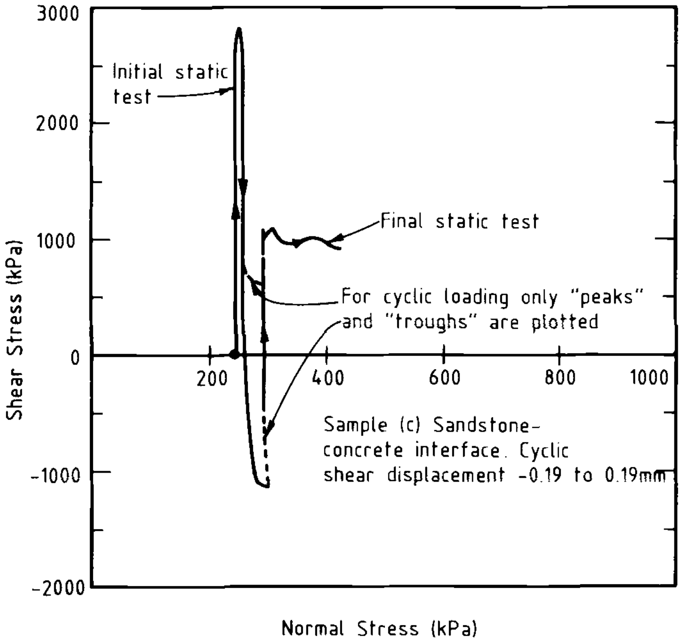


FIG. 12—*Stress path during cyclic test on Specimen c.*

0.15 mm/min), but it should be noted that the testing machine is capable of much faster cyclic shearing, as discussed previously.

From Figs. 10 and 11 it is evident that the specimen dilated during static loading to its peak shear strength and also during the first instance of reverse shearing from a displacement of approximately 0.35 to −0.19 mm (see also Fig. 8). Thereafter the changes in both normal displacement and hence normal stress with cyclic loading were only relatively small. The envelopes plotted on Figs. 10 and 11 indicate that during the early cycles there was some measurable difference in the normal displacement within each cycle but that beyond about 20 to 40 cycles the intracycle differences were extremely small. Figure 9, which is a plot of the envelopes of maximum shear stress applied to the specimen in each direction, also indicates that a relatively "stable" response was reached after about the same number of cycles, that is, the overall shear stiffness of the interface became nearly constant after about 40 cycles. It is of interest to note that the slight asymmetry, relative to the shear stress origin, of the curves in Fig. 9 indicates a slightly softer overall shear response in one direction (the one in which the shearing was first applied) during the early cycles. However, this situation is reversed at larger cycle numbers. After 100 cycles of the two-way displacement controlled shearing, a final static test was carried out. This involved monotonic shear displacement in the same sense as that for the initial static test. The post-peak cyclic shear strength was observed to be less than half of the peak strength during the initial static loading. Portions of the stress path during the static and cyclic phases of the test have been plotted in Fig. 12.

The results presented in Fig. 8 suggest that under displacement controlled cyclic loading this type of interface has undergone significant mechanical damage, that is, loss of shear stiffness and strength. This is despite the fact that some dilation occurred during the early cycles of the test. Furthermore, Figs. 10 and 11 tend to suggest that most of this damage was carried out during the first 20 or so cycles of reversal of shear displacement.

**Calcarenite Specimen**

The effects of cyclic shear loading on seabed materials has been a major concern for the designers of foundations for offshore structures in recent years. It was demonstrated above that one example of this type of natural material, namely, calcarenite, is prone to structural collapse, with a consequent decrease in porosity and shear strength when subjected to monotonically increasing shear loads. It is thus also of interest to investigate whether such behavior will occur when the material is subjected to repeated applications of direct shear loading of a magnitude less than the static shear strength.

Figures 13 to 17 present the results of a cyclic shear test on a specimen of calcarenite (Specimen d) in which the specimen was subjected to two parcels of cycles of one-way, load controlled cyclic shearing, with both being applied at a frequency of 0.083 Hz. (This frequency is consistent with that expected for the particular seabed foundations and is well within the capabilities of the testing machine.) In the first parcel the shear stress was varied sinusoidally with time between limits of 9 and 215 kPa. After 250 cycles at this stress level the specimen exhibited "shakedown" to a stable response, that is, the stage was reached where there was little or no further accumulation of shear and normal displacement with repeated load applications. These features are illustrated in Figs. 14 and 15. The specimen was then subjected to a second parcel of load cycles in which the shear stress was varied between 4 and 323 kPa. Mechanical damage of the interface because of repeated applications of this shear loading is evident from Figs. 13 to 16. Figure 14 indicates that an increase in cumulative shear displacement occurs with increasing number of cycles. Damage is also implied by the results in Figs. 15 and 16 where the gradual contraction of the specimen at the shear interface with increasing number of cycles is observed. This is accompanied by a corresponding reduction in normal stress. In this test failure occurred during Cycle 570 and

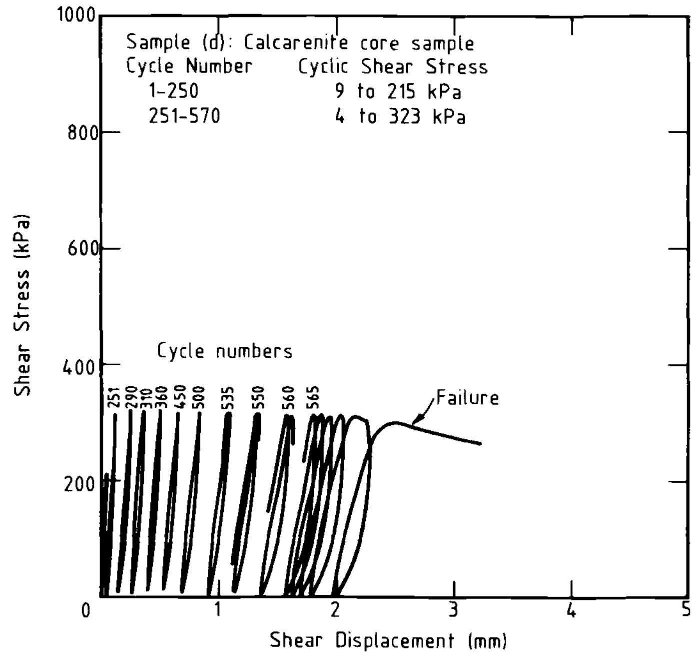


FIG. 13—*Shear stress versus shear displacement for cyclic test on Specimen d.*

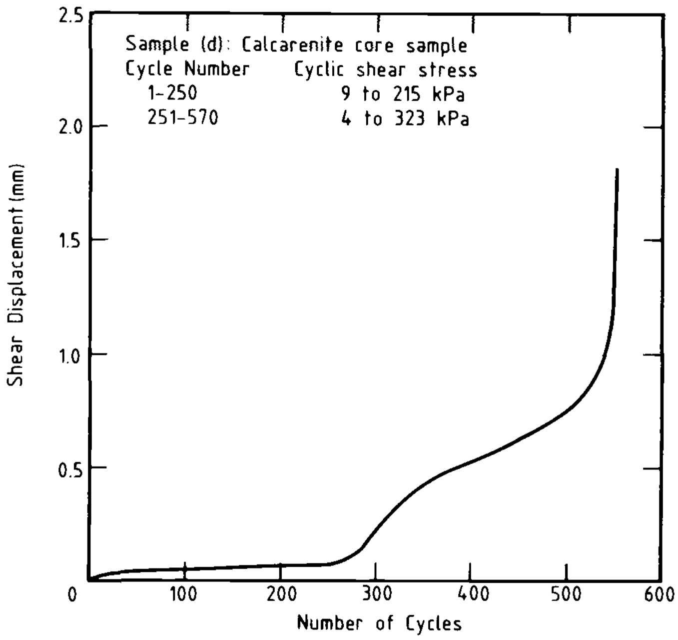


FIG. 14—*Cumulative shear displacement versus number of cycles for cyclic test on Specimen d.*

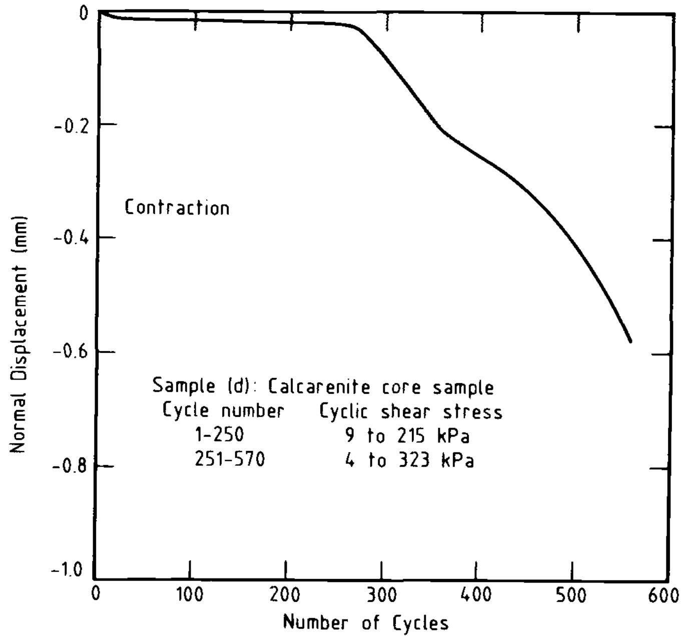


FIG. 16—*Normal displacement versus number of cycles for cyclic test on Specimen d.*

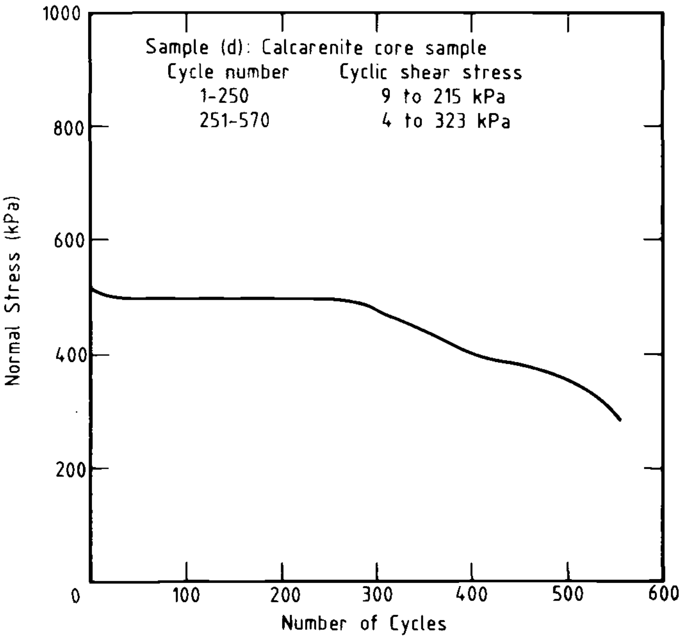


FIG. 15—*Normal stress versus number of cycles for cyclic test on Specimen d.*

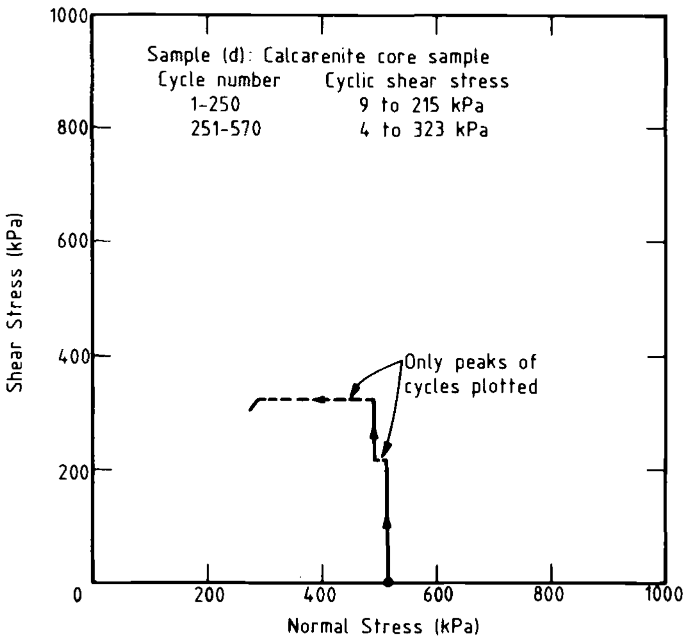


FIG. 17—*Stress path during cyclic test on Specimen d.*

was indicated by the inability of the servo-controlled testing machine to apply the programmed maximum shear stress during that cycle. Instead, there was a dramatic increase in the observed shear displacement.

Thus it has been demonstrated that shear failure may occur at an interface in this type of material under conditions of cyclic loading, even when the maximum shear stress applied in all cycles is below the peak strength of the material. The maximum shear stress applied to Specimen d was 323 kPa and yet Specimen b, which was a very similar material, indicated a much higher static strength of 510 kPa. For completeness the stress path followed by Specimen d during cyclic loading is indicated in Fig. 17.

## Conclusions

An apparatus that can be used for direct shear loading of soil and rock specimens or interfaces has been described. The apparatus is quite simple in concept and relatively simple to build and operate. When used in conjunction with a servo-controlled testing machine, it has the capability of applying both static and cyclic shear loading to the specimen by controlling either the shear load or shear displacement. The device has the special capability of applying a condition of constant stiffness in the direction normal to that of the shearing surface. Thus it is likely to provide conditions more representative of those in the field at a pile-soil or pile-rock interface, than would be the case in a direct shear test at constant normal stress. From the results presented in the paper it is clear that the normal stiffness can have a large influence on the shear strength of the interface whenever displacement in the direction normal to the interface accompanies the shear motion. This has been demonstrated for both cases of static and cyclic shear loading of interfaces composed of dilating and contracting materials. The normal stiffness condition is important because it influences changes in normal stress.

The important effects that cyclic loading have on the subsequent shear behavior of an interface have also been demonstrated.

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