The cellular raft and horizontal ground strains

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SUMMARY: The development of a cellular raft foundation (called the BOUCELL raft) is described and compared with the conventional slab-on-ground or stiffened raft foundation in a number of applications. The potential of the cellular raft to reduce the risk of distress to buildings caused by horizontal soil strain is discussed. Areas of application where this mechanism of horizontal soil strain should be considered, include:

- Buildings on ground to be undermined, particularly with longwall mining techniques for total extraction of coal.
- Buildings in seismically active zones where large ground motions may be involved.
- Buildings on swelling soft rock which has been weathered to considerable depth.

1. INTRODUCTION

Most of the low-rise buildings erected in South Africa are constructed with load-bearing brick walls and these walls are highly susceptible to distress in the form of cracks if they are subjected to differential movement. There has been continuous research over several decades in South Africa to develop economical foundation solutions for small structures, particularly in mass housing schemes, to cater for widespread problems caused by difficult soil conditions. Some of these natural and man-made problem soils or problem sites in South Africa include:

- **Heaving clay:** One of the major problems is that of "heaving clay" in the arid areas, or "shrinkable clay" in the seasonally more humid areas, and a number of viable solutions now exist (Williams, Pidgeon & Day, 1985).
- **Collapsing sand:** Vast areas in the more arid regions of the country are overlain by soils with a collapsible grain structure, or so-called "collapsing sand" (Schwartz, 1985). These soils can exhibit sudden differential settlement upon wetting up. They are often found to overlie a swelling clay profile, which complicates the matter further.
- **Dolomite:** There are large areas in the densely populated parts of the country that are prone to settlement on dolomite formations (Wagener, 1985).
- **Soft deposits:** In the more humid areas soft deposits, in the form of loose to very loose sand or soft clays, are encountered. Buildings constructed on these soft deposits may be subject to distress due to differential settlement.
- **Waste dumps or land fills:** With the increasing spread of urban development, the possible settlement of structures built on old waste dumps or land fills requires attention.
- **Undermining:** Where coal is mined at some depth below the surface and total extraction is employed, often with longwall mining techniques, there is considerable surface subsidence accompanied by large horizontal strains in the ground.
- **Seismic activity:** South Africa is not in a zone of high natural seismic activity (although significant events have occurred in the past), but many seismic tremors due to deep gold-mining activities cause distress in a number of areas.
- **Swelling rock:** A phenomenon not well recognised in the country as yet is the effect of deep underlying swelling rock on the performance of surface structures. In South Africa large areas of the country are underlain by such swelling rock.
- **High water table:** This is different kind of problem in the more humid areas of the country, where distress in the building consists mainly of rising damp in the walls.

From a socio-economic point of view, South Africa today faces other problems too. There is for example, a backlog in housing while mass urbanisation is taking place, and a shortage of skilled personnel capable of correctly analysing the potential effects of problem soils and sites. A need therefore exists for a foundation system that can easily be adopted as a blanket solution.

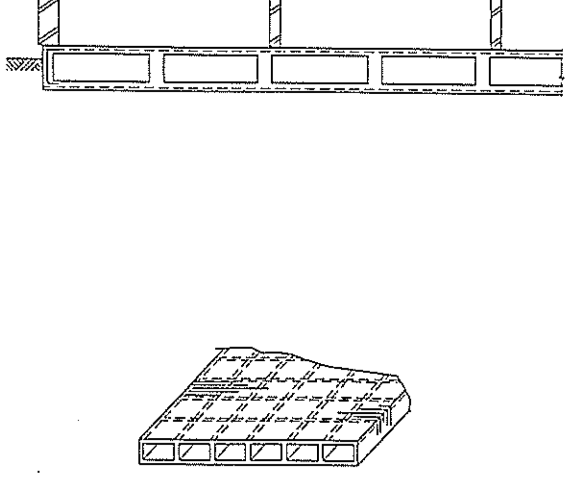

Fig.1. Cross-section of the BOUCELL cellular raft foundation

A variety of foundation and/or structural solutions has been developed, including piled foundations, stiffened rafts with articulated superstructures or methods for treating the soil to some depth (Barrett & Wrench, 1984). These methods all have advantages and disadvantages but none can be used as a solution for all problem soils.

Research and development at the Division of Building Technology of the CSIR has led to an improved cellular raft-like construction, which has been patented and is referred to as the BOUCELL raft. This cellular raft can be described as a traditional stiffened raft with an additional slab at the base (see Figure 1). Finite-element analyses comparing the stiffened raft and the cellular raft have confirmed that their structural behaviour is different.

The structural action of this cellular raft can be best described as simulating that of a composite sandwich panel. This foundation is several times stiffer, particularly in torsion, than the traditional stiffened raft with stiffening beams, because of the composite action of the top and bottom slabs with the integral webs. The advantages of the cellular raft compared with the traditional stiffened raft are discussed in more detail in Williams and Pellissier [1992] and include:

- Although dependent on geometry, the cellular raft is at least 2 to 4 times stiffer than the conventional raft in bending. Consequently, articulation joints in the superstructure can often be eliminated.

- The cellular raft shows an even greater increase in the torsional stiffness than in the bending stiffness. The result is that localised deformations are more effectively dealt with in the cellular raft, because the deformation is spread over the whole raft and is not localised as is often the case with conventional stiffened rafts.

- The cellular raft has the advantage that flexibility of architectural layout can be achieved as the webs are fairly closly spaced and the position of the internal walls is not governed by the position of the beams.

- With the cellular raft, the floor of the structure can easily be constructed above the surrounding soil, avoiding drainage problems caused by storm water or water-logged soil.

This new type of foundation is rapidly gaining ground as a blanket solution for problem soils and should be favoured in the coal mining areas, where the associated shales have weathered to become expansive clay near the surface. The potential ground movement in these areas can be fairly large - from a rise of 75 mm (caused by heaving clay) over the length of a house to a total mining subsidence of one metre, which could lead to very damaging differential movements in a house, or cause an unacceptable tilt. In such extremes the maximum horizontal displacement, expressed as a ground strain, could be 0.015 for longwall extraction of coal seams at depths of about 120 m.

In gold mining, where activities are very deep-seated, there are also effects of a seismic nature which may not reach the magnitude of major earthquakes but must be allowed for in structural design and consideration of soil/structure interaction. In this field, too, the cellular foundation could find useful application where a blanket option has advantages for a number of risks, whether from horizontal strains or motions, or vertical movements in the soil profile brought about by seismic activity. The advantages of this cellular raft foundation over the traditional stiffened raft (that is, increased stiffness in bending and torsion) apply to all the other problem soils where the vertical deformation of the soil is the overriding important factor.

This paper records the research carried out by the authors, highlighting the situation where horizontal soil strains can play an important role in the performance of the structure, and discussing the field and laboratory work carried out.

2. SEISMIC MOTIONS

2.1 Background

In South Africa very few earthquakes of medium intensity have been recorded, but between 40 and 60 tremors occur monthly in the gold mining areas (Milford and Wium, 1991). While the tremors are characterised by very high horizontal peak ground accelerations of up to 0.45 g (440 cm/s^2) with an associated ground velocity of 67 mm/s, the maximum frequency of the acceleration component is typically between 10 Hz and 50 Hz. The epicentres of these events are also relatively shallow (2 km to 4 km depth) and their effects attenuate very rapidly. Damage to residential type buildings in the mining areas has generally been limited to cracking of the plaster and brickwork, in accordance with the peak ground velocity rather than acceleration, where 10 mm/s seems to be a threshold below which there is little damage to masonry. This is a criterion often applied to acceptable ground velocities resulting from blasting with similar conditions of impact loading.

In regions subject to natural earthquakes where the strong ground motion of 0.5 g or more is random, the maximum frequency is low, say between 2Hz and 5Hz, and the disturbance is sustained for some time, perhaps up to 60 s or more. The horizontal component usually has the greatest effect on structures and according to Key (1988), "many failures occur in horizontal torsion, especially in low-rise garage-like structures that consist of a 'box' with one side omitted". Further, there seems to be evidence that the maximum ground strain at some distance from the source may be due to the secondary or slower surface waves, particularly Rayleigh waves where the horizontal component is parallel to the direction of propagation (O'Rourke, Castro and Hossain, 1984).

Horizontal displacements in low-rise buildings will be transmitted to the structure and consideration will have to be given to their dynamic response. For example, the design should reduce torsional effects, openings in walls should still permit adequate racking resistance, the roof should be light and the tops of the walls be well tied, and all connections should have adequate strength and ductility. However, the foundation will also be subject to horizontal movement and horizontal strains if the motions at two points are out of phase. The maximum soil strain, ϵ, is related to the velocity of propagation of the disturbance, C, and the peak particle velocity, V_{max}, as follows:

$$\epsilon = \frac{V_{max}}{C}$$

O'Rourke et al (1984) quoted an example of a bridge with abutments 21 m apart. If one uses values of $V_{max} = 34$ cm/s and C = 252 m/s (based on records from the San Fernando 1971 earthquake), the maximum differential displacement between the abutments is given as 27 mm. For a low-rise structure of similar dimensions, such as a bungalow with strip footings anchored into the ground, the displacements would have caused severe distress. In fact the ground strain of 0.13% exceeds the cracking strain of concrete (about 0.01%) and a slab-on-ground raft, anchored by stiffening beams, would have suffered.

A very good review of aseismic base isolation has been given by Kelly (1986), who points out that ground movement can be in any direction and that some mechanism to prevent movement in response to wind is needed. He mentions the approach adopted in China for low-rise concrete block or masonry buildings, which are very stiff and heavy, and hence at high risk for earthquake damage. A thin layer of specially screened sand is laid as a separation layer under the floor beams, above a wall foundation. He goes on to say that this idea of a sliding interface as an isolation system is "an attractive one for low cost housing since it can be constructed using no more complicated technology or no more skilled labour than a conventional building".

This review reveals that dynamic ground strains in the horizontal direction at the interface of foundation and soil can be significant, and many pictures of damage show cracks through foundation slabs or roads, indicating severe soil strain far removed from actual faults. However, other effects due to soil behaviour under earthquake-induced vibrations can also cause severe distress to any structure on or near the surface.

2.2 Soil behaviour under seismic conditions

One of the most catastrophic foundation failures can be caused by liquefaction of either granular deposits or stratified formations with thin layers of fine sand or silt. If the sands tend to consolidate during shaking and drainage is impeded, pore pressures in a saturated deposit will increase and there may be a sudden drop in the shear strength of the material, leading to liquefaction. Such behaviour can occur over wide areas and originate deep within the soil profile, so no normal foundations can cope with the situation. An engineering solution to such a problem could involve explosive compaction, dynamic compaction, or vibroflotation to bring the void ratio of the deposit down to a stable value.

Even if drainage was good, sandy soils or gravels would tend to compact under sustained shaking and give rise to compaction subsidence. There is bound to be some differential settlement and some stiff foundations or rafts might be able to cope with this if the total magnitude or tilt were still acceptable.

Seismic effects could also trigger slope instability by increasing the disturbing force, or increasing the lateral pressure on retaining walls. The ground movements could also induce failure in piles at their junction with the pile cap, unless the development of lateral pressures due to embedment of the cap helps resist displacement.

On the other hand, the frictional behaviour of soil can be exploited as a measure to reduce the peak acceleration transmitted through the foundation to the superstructure. A simple base-isolation system such as the cellular raft appears to perform well over a range of frequency and amplitude (Su and Ahmadi, 1989) and an important property is that the peak deflections of the structure do not vary much with increase in ground acceleration. The concept is that during a low-intensity earthquake the structure vibrates and returns to its original position after the seismic event.

During a higher intensity earthquake the structure may slip on the friction surface, several times if necessary, before coming to rest with some residual displacement, after much of the destructive energy has dissipated.

3. HIGH-EXTRACTION COAL MINING

3.1 Background

High-extraction coal mining has the advantage that a large percentage of the available coal reserves can be recovered, but the disadvantage that it causes surface subsidence. The financial benefits of this mining technique make it a popular method world-wide, in spite of the distress it can cause in surface structures. According to Bräuner (1973) it is convenient to describe the deformation at a surface point in terms of the five components: vertical displacement or subsidence; horizontal displacement; slope of the subsidence trough; curvature (vertical) of the subsidence through; strain in the horizontal directions, which can be tensile or compressive.

Various mathematical models have been developed to predict the movement of the soil surface, but the local geology, depth, width and height of extraction have such an important effect on the subsidence profile that can develop on the surface, that each prediction model has to be calibrated for each mine. However, according to Bräuner (1973) tensile and compressive strains cause most mining damage. The main effects of these horizontal strains are tensile fractures, shear (compressive) fractures and the squeezing or buckling of structural elements.

Strains can be expressed as a percentage, or millilmetres per metre and (as used in this paper) as a dimensionless quantity. According to Bräuner (1973) the maximum strains in single troughs are from 1×10^{-3} to 10×10^{-3} and this is more than an order higher than the cracking strain of concrete and brickwork, which is about $0{,}1 \times 10^{-3}$ (or 0.01 %).

3.2 Structural requirements

A suitable foundation system should therefore either be able to resist all the horizontal forces, or allow slip to occur between the soil and the superstructure. The ribs of the conventional stiffened raft are deeply bedded into the soil and this type of foundation should therefore be designed to resist all the tensile forces, whereas the flat soffit of the cellular raft allows for a slip-surface.

The Subsidence Engineer's Handbook (1975) recommends a flexible structure where the foundation slab is cast on a polythene sheet on top of a friable layer, such as 150 mm or more of sand. However, it is questionable whether this kind of foundation would be suitable in South Africa where the coalfields are associated with highly expansive clay deposits (Pellissier 1990). These require stiff foundations to reduce the differential movement to levels that can be tolerated by the superstructure. Also, the curvature induced by near-surface coal mine extraction can be severe if hard rock overlies the mining works.

The cellular raft can be considered the optimum solution for small structures in areas with swelling surface clay, or for prevention of distress due to coal-mining subsidence, for the following reasons:

- It provides the stiffness required to reduce differential movement.
- A slip plane can easily be provided under the flat soffit.
- If the final slope of the building after undermining proves to be unacceptable the foundation normally has enough stiffness to allow the one side of the building to be jacked up to get it level again.

4. DEEP UNWORKED RESIDUAL CLAY

In Pellissier and Vogler (1990) "deep unworked residual clay" was described as deep residual swelling material ranging from stiff clay to very soft rock, where the joint structure of the original parent rock can still be seen. As discussed in the above reference and in Pellissier (1991), these materials cover a large part of the country and exhibit unique swelling properties. The swell of these materials is less affected by the overburden load, with the result that swell at 20 m depth can still affect the performance of the superstructure significantly.

In normal, shallow, surface clay the effects of horizontal swell strains are ignored as far as the design of the foundation is concerned. However, as discussed in Pellissier and Williams [1991] horizontal tensile stresses were observed in the beams of conventional stiffened rafts constructed at a swelling clay test site at Onderstepoort near Pretoria. Field evidence also indicates that the effect of horizontal swell strain caused by these deep clays can affect the performance of the building and the design of the foundation. In a discussion of the distress in a school near Springs founded on these materials, Meintjes (1991) remarked that the ratio of differential vertical displacement to differential horizontal displacement was in the range of 3/8, with the result that the one metre deep reinforced concrete ground beam failed in tension, and 20 mm tension cracks developed in it.

All the requirements discussed for mining subsidence would therefore also apply to these deep unworked residual clays.

5. CELLULAR RAFT CAPABILITIES

5.1 Theoretical assessment

The horizontal strains discussed above can be compressive or tensile and, if compressive, the perimeter of the foundation may also be subject to passive earth pressures. It is therefore advisable that the foundation be as shallow as possible to reduce the risk of distress from compressive soil strain. However, brickwork and concrete structures can normally resist compressive pressures or strains, but they are less suited to resist tensile stresses, or strains which are often larger than the cracking strain of brickwork or concrete.

An effective way of reducing the risk of distress to buildings would be to reduce the tensile soil strains transmitted to the superstructure by the foundation. Under conditions of horizontal soil strain, piled and conventional stiffened raft foundations could also experience problems, because they are firmly bedded in the soil and do not allow slip between the foundation and the soil.

However, if required, the flat soffit of the cellular raft foundation can allow slip between the soil and the foundation. As the ground deforms the horizontal component causes shearing movement underneath and along the side walls of the foundation; these frictional forces should be resisted by the raft. A certain amount of relative displacement between the raft and the soil is required to develop the maximum shear stress, which then stays constant for further relative displacement. The typical development of shear stress can be seen in Figure 2.

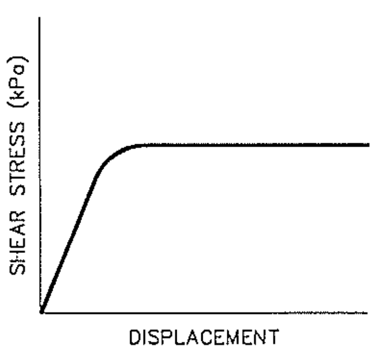

FIG.2. Relationship between friction force development and relative displacement

To analyse the transfer of frictional forces to the raft foundation the foundation may, in simple terms, be considered as a linear structure of unit width (see Figure 3) and perfectly rigid in terms of its reaction to horizontal forces applied along its length. It is also assumed that the middle of the raft will be displaced along with the ground motion (i.e. there is no relative displacement between the soil and the raft at the raft's mid-point). Away from the middle of the raft, increasingly larger relative displacement occurs between the raft and the soil. It is further assumed that the relative displacement decreases linearly towards the middle of the raft. Finally, it is also assumed that there is uniform contact-pressure distribution under the raft.

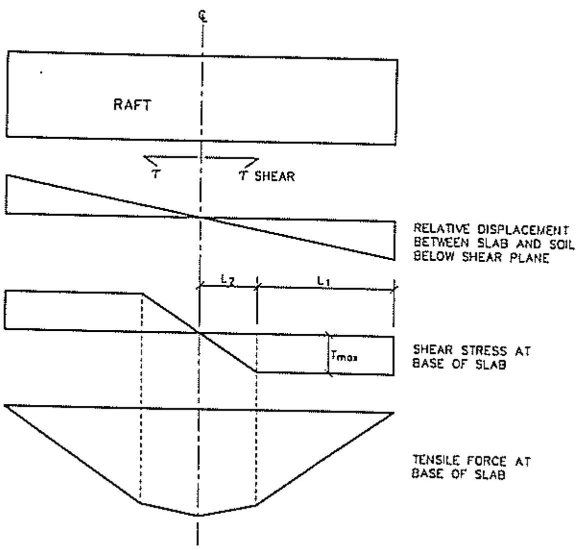

FIG.3. Friction forces acting on the underside of a raft foundation subject to horizontal tensile soil strains

The friction tensile force transmitted to the raft accumulates in its transverse section and increases bi-linearly towards the centre, and the maximum force occurs in the middle. Based on all these assumptions Ren (1988) suggested the following equation to calculate the maximum tensile force (see Figure 3 for detail):

$$F_{max} = T_{max} \cdot L_1 + \frac{1}{2} \cdot T_{max} \cdot L_2 \qquad (1)$$

where

F_{max} = maximum tensile force in the raft due to lateral extension

T_{max} = maximum shear stress at the contact between the raft and the soil

L_1 = length over which the maximum shear stress applies

L_2 = length over which the shear stress increases linearly.

The shear strength/displacement relationship of undisturbed soils often exhibits a high peak shear strength, before dropping to a lower residual shear stress value. However, during the preparation of the flat surface for the construction of the cellular raft, a thin layer of soil would normally be disturbed under the foundation. T_{max} in equation 1 should therefore approximate the residual shear strength of the soil.

In the analysis of the shear stress build-up under a conventional stiffened raft it should be taken into account that the ribs of the raft may extend well into the soil and that the larger part of the soil remains undisturbed. Peak shear stresses may therefore develop under a conventional raft and equation 1 should therefore be written as:

$$F_{max} = T_{res} \cdot L_1 + \frac{1}{2} \cdot T_{pek} \cdot L_2 \qquad (2)$$

where
T_{res} = residual shear strength of the soil
T_{pek} = peak shear strength of the soil.

The length over which the shear stress increases (L_2) can be calculated as follows:

$$L_2 = \frac{L_0}{\epsilon_s} \qquad (3)$$

where
L_0 = relative displacement required for maximum shear stress development
ϵ_s = horizontal ground strain as a dimensionless value.

The value of L_0 can be determined using a laboratory shear-box, and the value of the horizontal ground strain should be predicted for design purposes. It should be noted, however, that under conditions of small horizontal soil strain the maximum shear stress (T_{max} or T_{pek}) under the raft may never be mobilised.

5.2 Field and laboratory tests to investigate shear transfer

Field and laboratory simulation tests were carried out to investigate various practical conditions, as well as methods of reducing the risk of distress to buildings subject to horizontal soil strain. To investigate the transfer of stress to the bottom of the raft, three small experimental rafts were constructed at the CSIR Test Site in Pretoria and they consisted of:

- A cellular raft with plan dimensions of 2 m × 2 m, cast in situ on the flat soil surface.
- A cellular raft with plan dimensions of 2.6 m × 2.6 m, placed on top of a special slip layer. The slip layer consisted of a 3 mm rubber-bitumen layer, sandwiched between two plastic sheets.
- A conventional stiffened raft with plan dimensions of 2.6 m × 2.6 m, cast in the soil.

All the experimental rafts had a depth of 600 mm and they were loaded with concrete blocks, so that all of them had an average contact pressure of 15 kPa below the concrete slab. Since it was the development of shear stress beneath the rafts that was to be investigated, the soil at the edges of the rafts was excavated and removed to prevent passive earth pressures from developing. Hydraulic jacks were used to used to move these foundations horizontally, load cells were used to record the force required to do so, and LVDT's were used to record the movement.

The results of these tests can be seen in Figure 4. As expected, the cellular raft placed on a rubber-bitumen emulsion showed the least resistance to movement, and the conventional stiffened raft the highest. It can also be seen that shear stress development under the conventional raft showed a peak value before dropping off, while the cellular raft cast on the soil sheared at a lower shear stress, probably the residual shear strength of the soil.

The lowest coefficient of resistance was 0.44. This is, however, still higher than the ideal value of 0.2 suggested for conditions of seismic activity and an alternative product would therefore be required for these situations. A viscous type of material was sought that would offer a resistance of about 3 kPa in shearing at a velocity of 10-30 mm/s and it was hoped that a quick-breaking bituminous emulsion would be suitable, but this was not practical. A more viable option seems to be a cutback bitumen of MC 3000 grade with a viscosity of about 2000 poises for a 1 mm thickness or about 4000 poises for a 2 mm thickness. This material could then be applied between two layers of plastic sheet beneath the raft and would serve the additional purpose of providing a good damp-proof membrane.

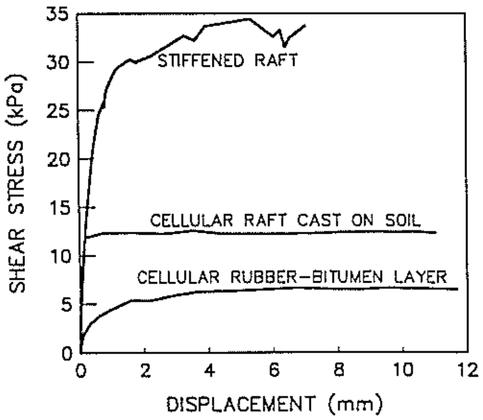

FIG.4. Results obtained from the jacking of experimental rafts

Shear-box tests simulating the field conditions were also carried out in 102 mm × 102 mm square shear boxes and in all cases vertical loads of 7.3, 15.7, 25.2 and 35.1 kPa were applied. The tests simulated the following conditions:

- Shear through the in situ soil. The natural soil does exhibit a collapse potential and, as it is difficult to simulate the in situ condition correctly, remoulded specimens were used, compacted to a density of 1 800 kg/m³ at 8 % moisture content. Further, these remoulded specimens could not model the cementation between the soil particles, with the result that the maximum shear stress was probably underpredicted.
- Concrete cast on soil. This was simulated in the shear boxes by preparing a remoulded soil specimen in the bottom half of the shear box and casting a small concrete block in the top half.
- Shear through the rubber-bitumen layer. This was simulated by preparing a remoulded specimen in the bottom half of the shear box, placing the sandwich layer of rubber-bitumen between plastic sheets and then placing a steel loading plate on top of it. Shear movement thus occurred through the sandwich layer.
- Shear between different plastic layers. Tests were also carried out to study the reduction in shear stress if several plastic sheets were placed under the raft.

The results of all these tests are given in Figure 5. The results obtained from the field test are also given in the figure and although some discrepancies exist between the field and laboratory results, the pattern of shearing resistance is clear. Note, however, that while the contact pressure below the slabs was 15 kPa, the weight of the soil between the ribs of the conventional raft contributed an additional 9 kPa to the pressure on the shear plane at the base of the beams.

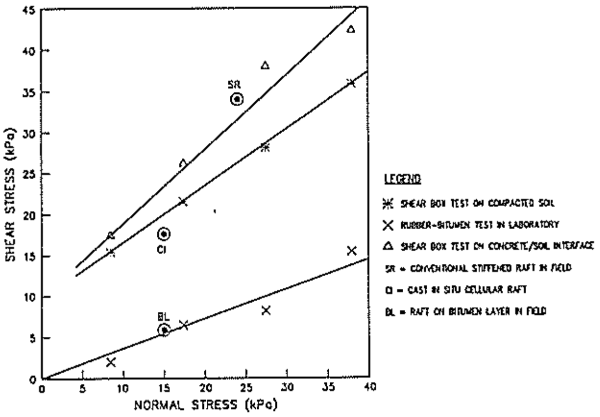

FIG.5. Laboratory shear-box test results of simulated conditions

6. DISCUSSION

Many small structures do not warrant a detailed analysis of potential structural performance under all the possible risk conditions that may be encountered during their lifetime. Further, there is often a combination of problems due to a complex soil profile, or unpredictable loading conditions. For such cicumstances an economical solution has been sought, particularly in developing regions where an absence of expertise may prevent recognition of the problems at an early stage.

The cellular raft foundation was originally conceived during a study of problems related to regional subsidence and large ground strains. The concept was then applied to the widespread difficulties encountered with heaving clays, and several successful schemes have now been completed. It was realised that it might have applications in areas of seismic activity and a few preliminary studies in the laboratory and on a test site have indicated that a base-isolation system might be developed satisfactorily. A literature survey encouraged the development of such a concept. It is not possible, however, to implement such a study on a full scale in South Africa because of the (fortunate) infrequent occurence of major seismic events to date. Further research and development in this respect seems warranted.

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