The Geodynamic Approach

problem or possibility?

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The geodynamic approach - problem or possibility?

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SYNOPSIS: The Danish National Lecture - *The Geodynamic approach - problem or possibility?* - mirrors the authors involvement in projects and research focusing on the impact of the geodynamic approach. The lecture discusses the why and how of some of the geotechnical anomalies and the differences in traditional static and dynamic approach. Examples of current projects with geodynamic focus are briefly presented together with the available equipment and methodology. The role of interplay with other geodisciplines and the possibilities in the geodynamic approach conclude the lecture.

1. INTRODUCTION

The topic for this lecture was dictated by recent experience with design of very large structures and the research focus of the Aalborg University Geotechnical Engineering Group. In both cases attention has been drawn to the impact on design and importance of dynamics (Figure 1).

Traditionally, the special cases - the exceptions or anomalies - have attracted most of the attention in geotechnical engineering. Examples are (indicating reality/generality in italics)

- plane strain problems • *3D problems*
- undrained conditions • *some degree of drainage*
- axisymmetric testing • *3 D conditions*
- strain controlled testing • *load controlled reality*
- normally consolidated conditions • *some degree of overconsolidation*
- static loading conditions • *dynamic loading*

This bias is understandable as the special cases often allow a more direct approach and are dictated by the possibilities offered in terms of analytical solutions, test equipment and numerical tools.

However, this bias may also have been responsible for some of the anomalies discovered when comparing reality with prediction.

In the real world the special cases are at best permissible approximations and at worst, cases clouding the understanding of the physical phenomena responsible for the observed behaviour.

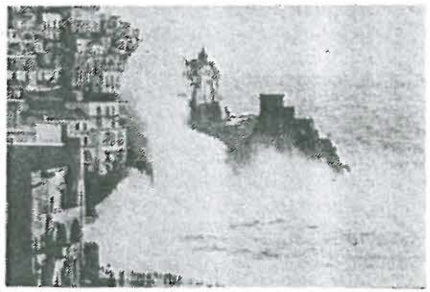

Fig. 1 Dynamic wave loading, Amalfi, Italy

In recent years is has been realised that geodynamics is not a special case of loading to be considered for earthquake engineering or for vibrating machinery, but rather the fundamental loading case. Static loading is the special case, albeit a very appropriate approximation for a large number of situations.

However, the important point is that if the dynamic nature of the loading is disregarded the underlying mechanisms and the fundamental soil response may easily be misinterpreted.

As an example consider the discrepancy between the modulus of elasticity found by dynamic tests and traditional static laboratory tests. When analysed correctly, it turns out that there is no difference, but rather a difference in strain levels, i.e. a demonstration of the difference between small and large strain problems.

2. WHY ANOMALIES?

There are a number of reasons for the wide spread acceptance of the anomalies. Very often the simplification embedded in the anomaly allows for a direct approach or is directed by the shortcomings in capabilities of 3D analytical or numerical analysis and testing. Importantly, experience has proven some of the anomalies to be viable approximations, whereas other cases merely reflect traditional approach or mere ignorance.

Thus, we need to check on the use of the special cases - the anomalies:

- Is there some reason for the embedded approximation in terms of availability, or cost and time limitation?
- Can the approximation be checked, i.e. are full scale experimental or numerical evidence at hand?
- Is the underlying physical nature of the problem understood and reflected in the approximation at hand?
- Could the general case in fact be considered?

Before we can answer these questions satisfactorily we may have a problem in terms of safety and economy of the structure resulting in our design approach.

3 SOIL DYNAMICS

The origin of soil dynamics is clearly in earthquake engineering (see Figure 2), which prompts the need for understanding the behaviour and role of soil masses during earthquake shaking.

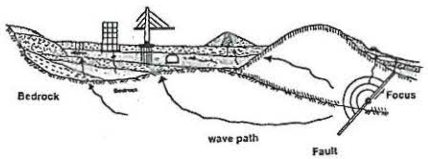

Fig. 2 The earthquake engineering problem (after Gazetas, 1987)

Here the forces of inertia play a decisive role for both action and resistance. However, there is a smooth transition from dynamic to static type problems and the static solution may serve as a viable reference point, in the least as a means to linking existing design experience to the more complex geodynamic approach.

In contrast to structural dynamics, however, soil dynamic problems involve semi-infinite geometries and masses continuous in two or three directions.

Examples of applications of soil dynamics are:

- Geotechnical earthquake engineering (see Figure 3).
- Vibration induced by machine foundations.
- Wave-induced oscillation of offshore structures (see Figure 4).
- Impact loading (ship or ice collision with bridge piers).
- Effects of explosions.
- Traffic and rail induced vibrations (important with the surge in infrastructures in Europe and the advent of high speed trains).

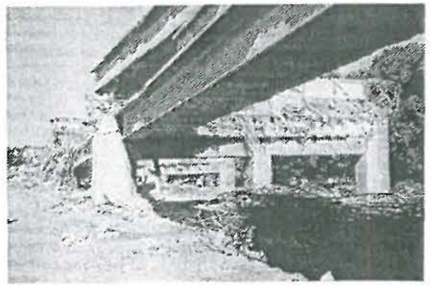

Fig. 3 San Francisco earthquake 1989. Collapsed two-storey highway (Photo: N.K. Ovesen)

- Pile-driving induced settlements and vibrations.
- Densification by vibratory or impact loading.
- Geophysical soil exploration (probably one of the most promising areas of positive use of soil dynamics).

4. SOIL DYNAMICS VERSUS MECHANICS

Some of the distinct differences between problems clearly involving soil dynamics and the traditional soil mechanics are listed in Table 1.

The geotechnically important case of cyclic loading may be considered as an intermediary problem.

The ultimate case of static loading may be seen as the pyramid where the load is almost constant over millennia (see Figure 5), whereas the deterrent display in Abha, Saudi Arabia (Figure 6) may serve as a reminder of the very different nature of dynamic or impact loading.

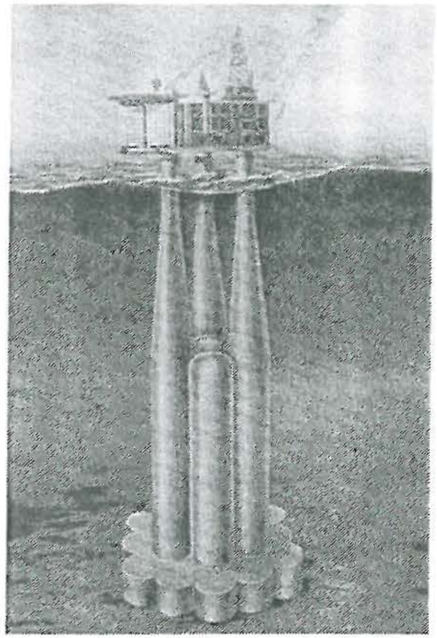

Fig 4. Artists view of Troll platform (courtesy NGI)

Table 1. Differences in dynamic and static approach

Item	Soil dynamics	Soil mechanics
Boundary loading	Variation with time	No variation or monotonic
Boundary stresses and strains	Of cyclic nature	Monotonic
Spatial distribution of stresses and strains	Governed by wave equations	Governed by equilibrium equations
Inelastic-hysteretic behaviour	Key importance	Often disregarded
Determination of loading	Integral part of solution	A priori given

Fig. 5 View of the Pyramids at Giza, Egypt

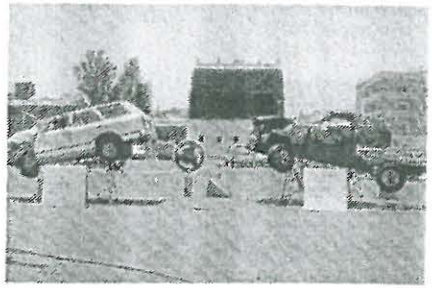

Fig. 6 A warning display of crashed cars, Abha, Saudi Arabia

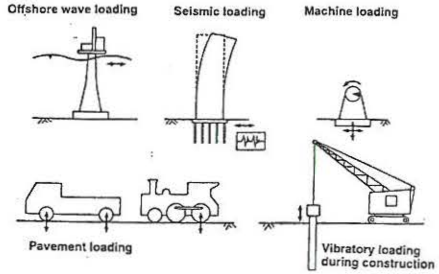

Fig. 7 Examples of significant cyclic/dynamic loading (after O'Reilly and Brown, 1991)

5. GEODYNAMIC PROJECTS AT AAU

Some of the projects currently being investigated by the Geotechnical Engineering Group at Aalborg University may illustrate elements in the geodynamic approach.

As described previously, and shown in Figure 7, a number of structures are experiencing significant cyclic/dynamic loading. To provide a safe and economic design for these structures it is of prime importance to establish relevant soil parameters for the use in the dynamic analyses.

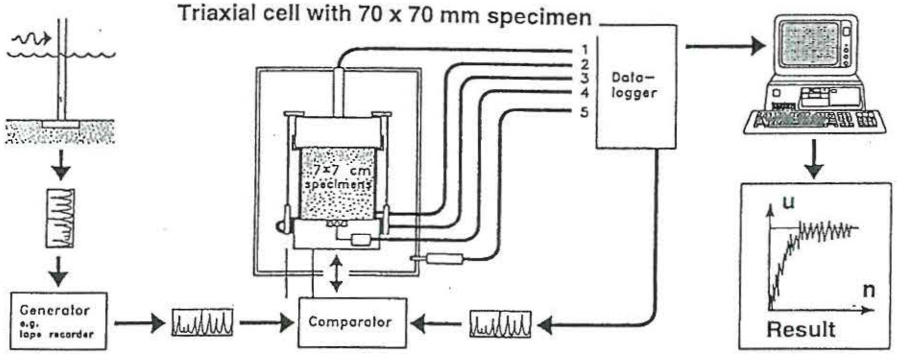

Fig. 8 Schematic view of AAU dynamic triaxial set-up

To qualify and quantify the effect of the dynamic loading dynamic element tests play a major role. Here we resort to some of the anomalies mentioned in Section 1 in order to gain sufficient control over test conditions to be able to isolate significant effects of the cyclic/dynamic loading.

5.1 *Example 1: Dynamic element testing*

The AAU dynamic triaxial apparatus is shown schematically in Figure 8.

The triaxial set-up, presently taking 70x70 mm cylindrical specimens, is load- or strain controlled, using a hydraulically operated load piston. The range of possible strain rates is from 0 to 100,000 % per hour. Impact loading may thus be investigated. For research purposes sinusoidal, triangular or square loading sequences are used, but the set-up allows prerecorded load sequences (from real structures) to be applied, i.e. the effect of load parcels involved in storms or the like may be investigated.

Based on the long-term Danish experience with static loading triaxial test set-ups a height/-diameter ratio of one and smooth pressure heads are maintained for the dynamic set-up as the type of testing and equipment play a major role on the soil parameters produced.

In element testing it is extremely important that the test conditions are well defined and hence, ideally the strain conditions should be as close to homogenous as possible. This is only obtained when a height/diameter ratio of 1 and smooth pressure heads are used.

The differences in results for specimens with height/diameter ratios of 2 and 1 are illustrated in Figure 9 for static loading. Undrained tests with H=2D deviate considerably from H=D undrained behaviour as they show pronounced peak behaviour and lower (and even misleading) undrained strength values.

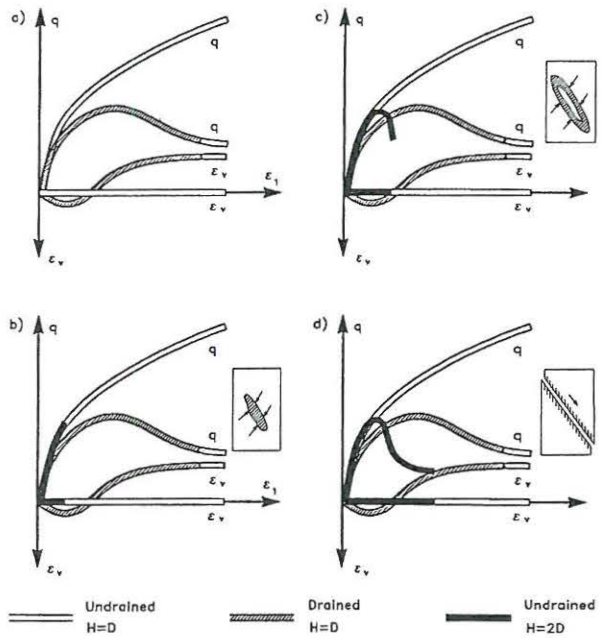

Fig. 9 Schematic illustration of differences in behaviour of undrained tests on H=D and H=2D specimens (after Ibsen, 1993a)

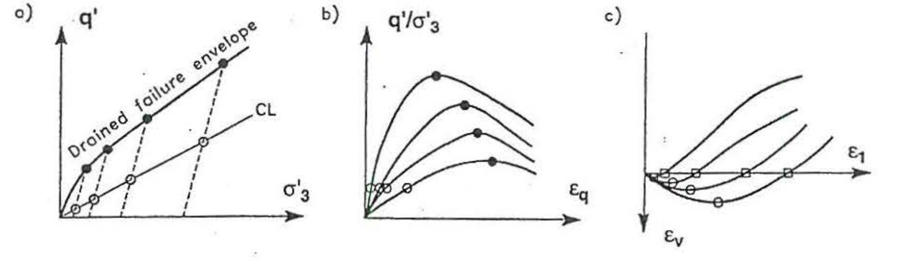

Fig.10 Results of drained CD tests on dense sand for H=D specimens at different confining pressures. CL indicates Characteristic Line (after Ibsen, 1994)

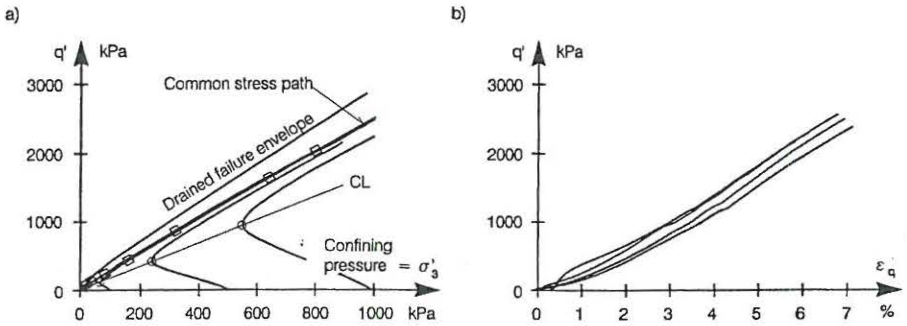

Fig. 11 Results of undrained $CU_{u=0}$-tests on H=D specimens of Lund 0 sand with I_D=0.78 (after Ibsen, 1994)

So far the research in the dynamic triaxial set-up has focused on examining the behaviour of sand. Static drained CD-tests (see Figure 10) and undrained $CU_{u=0}$-tests (see Figure 11) serve as backbone tests for dynamic testing. They provide information on the position of the Characteristic Line, CL, separating the regimes of contraction and dilation or regimes with positive and negative pore pressure build-up and limits the regime of permissible stresses (cf. Figures 10, 11).

It should be noted that more recent research indicates that the Characteristic Line may be stress-path dependent and hence, not unique.

In static undrained tests, conducted as $CU_{u=0}$-tests, failure is not observed, but the stress paths tend to follow a common stress path at increasing stress level (not valid for very high pressures where grain crushing plays an important role).

The dynamic tests are carried out as CU-tests as $CU_{u=0}$-testing only works at lower strain rates. For the tests in Figure 12 no back pressure was applied, and hence the development in deviator stress q is limited by $u \geq -100$ kPa in the pore water. This is observed as a transition from the common stress path to the drained failure condition.

Figure 13 shows the results of a series of dynamic triaxial tests with strain rates ranging from 40 - 10,000% per hour.

No rate effect on the dynamic strength is observed for this strain range (but an effect on the stress-strain behaviour is seen in Figure 13b).

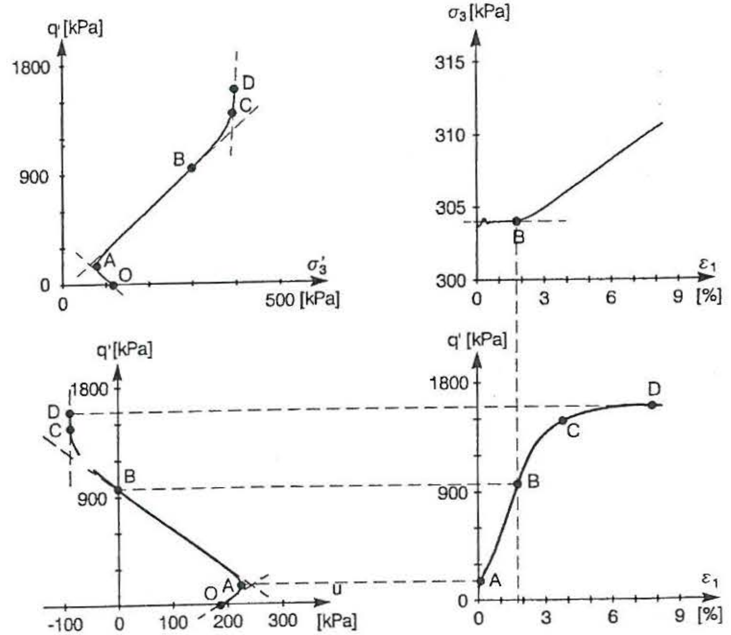

Fig. 12 Results of undrained dynamic CU triaxial tests on H=D specimens of Baskarp 15 sand with I_D = 0.78 at a strain rate of 1000 %/hour (after Ibsen, 1995)

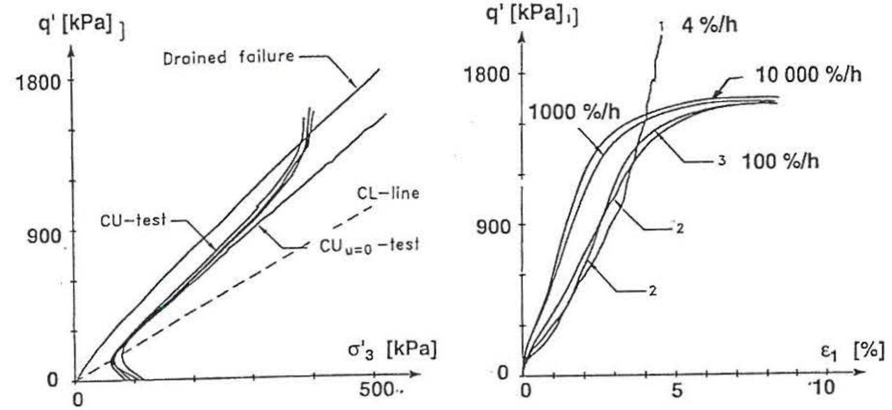

Fig. 13 Results of dynamic CU tests on H=D specimens of Baskarp 15 sand at I_D = 0.8 at different strain rates. Note, that the static test, 4%/h, is carried out as a $CU_{u=0}$- test! (after Ibsen, 1995)

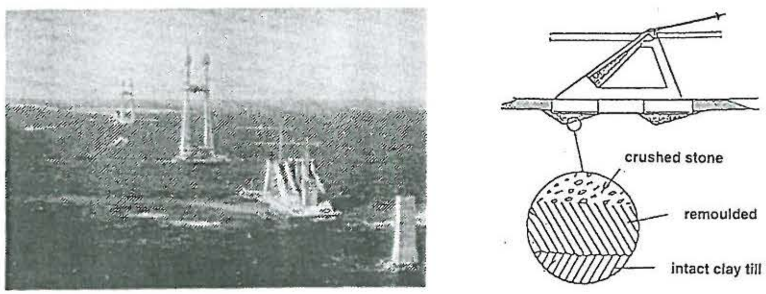

Fig. 14 Storebælt sliding problem for anchor blocks on clay till (after Steenfelt, 1992)

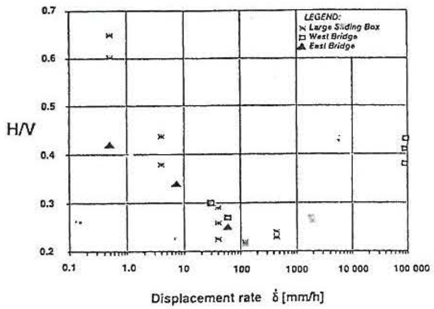

Fig. 15 Variation of sliding capacity H/V with displacement rate $\dot{\delta}$ for Storebælt sliding tests (after Steenfelt, 1992)

This is in sharp contrast to the findings in clay where a strain rate dependence of some 5 - 10% per log cycle of time increase is reported in literature. This was confirmed at AAU for triaxial tests on clay till for the Storebælt Link Project and by the investigation of the sliding problem for Storebælt bridge piers and anchor blocks (see Figure 14).

However, as seen in Figure 15 a trough-shaped dependence of sliding capacity H/V (or stress ratio τ/σ) on sliding rate $\dot{\delta}$ was found for the sliding tests.

This exemplifies that the undrained state in the field is most likely a misnomer and that we must be very careful when comparing laboratory element tests and field or full scale tests.

The degree of confinement is most likely the decisive parameter. A complete confinement can be obtained in the laboratory allowing undrained conditions, but this will in practice never be possible in the field.

Dynamic capacity of bridge piers on limestone

In 1996 the question of dynamic capacity for ship impact was a hot issue for bridge piers and pylons of the Øresund Link bridge founded in Copenhagen Limestone. The characteristics of the limestone are shown briefly in Figure 16. Preliminary sliding tests on chalk with roughly the same characteristics as unlithified limestone (H1) show a rate dependence on sliding capacity, but qualitative different from clay till behaviour.

Due to much higher hydraulic conductivity of the limestone the test set-up could not provide the extremely high strain rates to truly mimic the dynamic loading.

5.2 *Example 2: Fatigue model for sand*

With a clear link to the design of offshore structures (f. inst. Figure 17) a lot of effort has been channelled into establishing a "fatigue" model for sand.

- **Strength model - Øresund Link**
  Predominant soil/rock type for foundation works, dredging, and reclamation
- **Silty to sandy limestone**
  - strongly varying induration
  - flint as continuous layers or nodules
  - strongly varying matrix strength
- **Strength**
  - Unlithified lime (H1 ≈ R0) $\sigma_c \approx 0.25 - 1$ MPa
  - Flint (H5 ≈ R5-R6) $\sigma_c \approx 100 - 400$ MPa

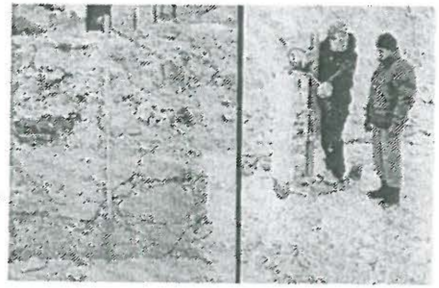

Fig. 16 Characteristic of Copenhagen Limestone and sample retrieval at Lernacken, Sweden

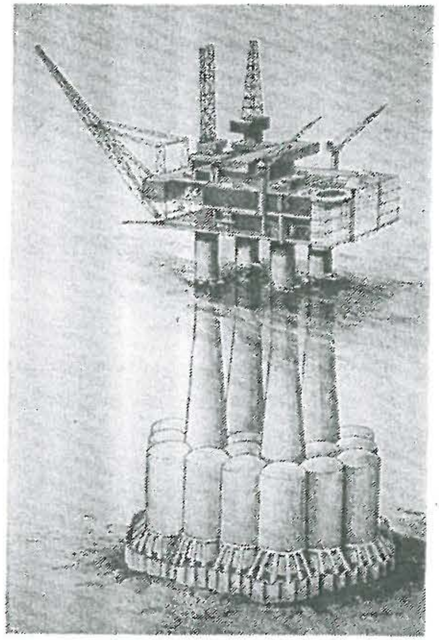

Fig. 17 Offshore gravity platform

At the same time the research aimed at elucidating and qualifying the risk of liquefaction associated with cyclic/dynamic loading in general.

Figure 18 shows an example of a cyclic triaxial test on sand with H=D. It shows, in contrast to H=2D type testing, that a stable state rather than liquefaction is obtained.

Based on a large number of tests with different cyclic load parcels, as shown in Figure 19, the existence of a Cyclic Stable Line - a state boundary line - was established.

When the stress path reaches the cyclic stable line, the mean normal effective stress remains constant independent of the number of load cycles.

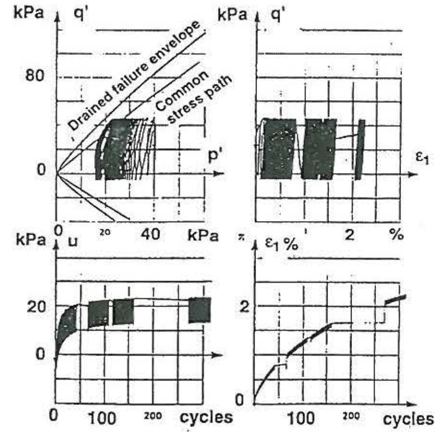

Fig. 18 Cyclic triaxial tests on H=D specimens of Lund 0 sand, $I_D = 0.78$ showing pore pressure build-up (after Ibsen, 1994)

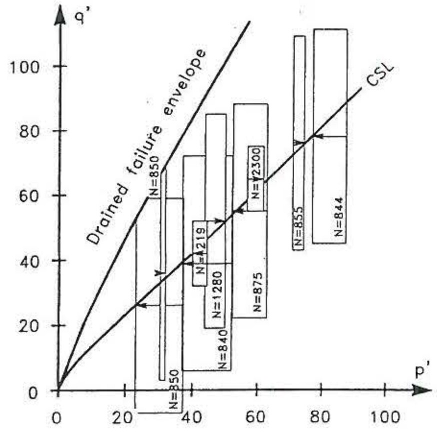

Fig. 19 Effective stress paths for cyclic tests on H=D specimens of Lund 0 sand, I_D = 0.78. N indicates the number of cycles in the load parcel (after Ibsen, 1994)

The tests have further led to the formulation of a cyclic degradation theory (H=D tests) which allows prediction of the behaviour of each soil element depending on the average shear stress level, the cyclic shear stress, and the number of cycles (cf. Figure 20).

The different, simplified stress conditions experienced by different soil elements beneath an offshore foundation are shown in Figure 21 together with the different types of outcome from the cyclic degradation model.

In general, application of these findings indicate that the cyclic loading may in fact result in increased safety level as exemplified by Figure 22, where negative pore pressure changes result during undrained conditions below an offshore foundation during a short storm period.

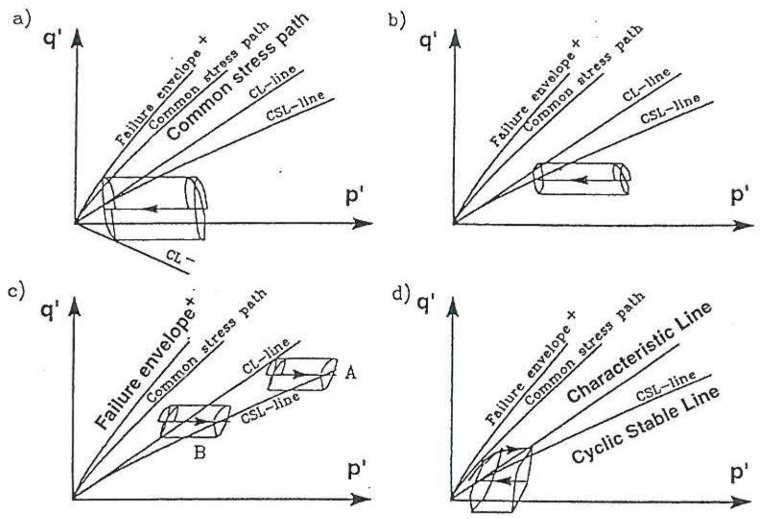

Fig. 20 Phenomena associated with cyclic undrained triaxial tests on H=D specimens of sand. (a) Cyclic liquefaction; (b) Pore pressure build-up; (c) Stabilisation; (d) Instant stabilisation (after Ibsen, 1994)

However, dissipation of pore pressures still needs to be added to the model to reflect real behaviour.

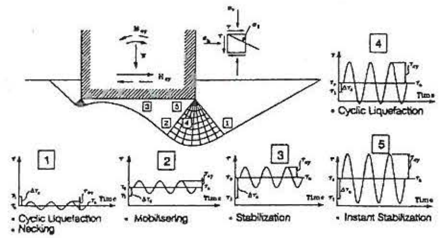

Fig. 21 Simplified stress conditions under foundation subjected to cyclic loading (after Ibsen, 1993b)

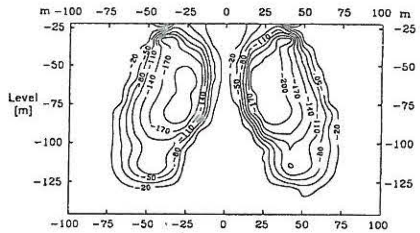

Fig. 22 Pore pressure changes due to cyclic loading of an offshore foundation (after Ibsen, 1993b)

5.3 *Example 3: Impact loads on foundations and caisson breakwaters*

Figure 23 shows a typical cross section of a caisson breakwater on rubble mound.

In the design of such a break water the impact load is crucial and the key question is: How much will the caisson move?

A study has been initiated where the dynamic capacity of foundations is found based on well known static failure mechanisms (on the basis of the theory of plasticity) but with full account of the forces of inertia in the work equation. Furthermore, the load-time characteristics, seen in Figure 24, are taken into account.

As a result the dynamic calculation for impact loading can provide the horizontal movement of the caisson with due account of the stain rate dependent increases in undrained shear strength for foundations on clay profiles.

The research is part of a current EU funded MAST programme (Marine Science and Technology).

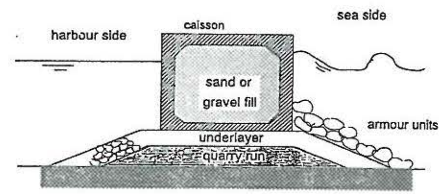

Fig. 23 Schematic cross section of caisson breakwater on rubble mound

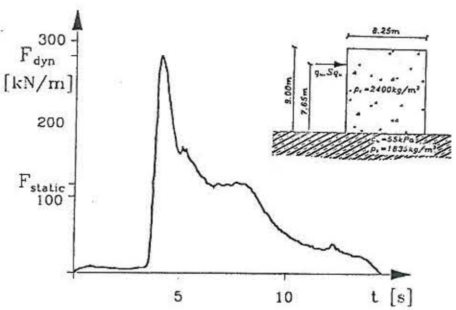

Fig. 24 Load-time characteristics for wave impact on a caisson breakwater on clay (after Ibsen & Jakobsen, 1997)

6. EQUIPMENT AND METHODOLOGY

With the advent of cheaper and more powerful computers, data acquisition units and signal processors, it has been possible to develop laboratory and field test equipment to provide soil parameters for design using the geodynamic approach.

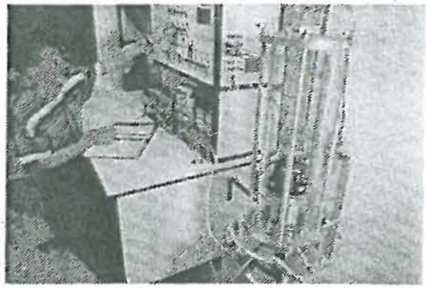

Fig. 25 Resonant column set-up at AAU

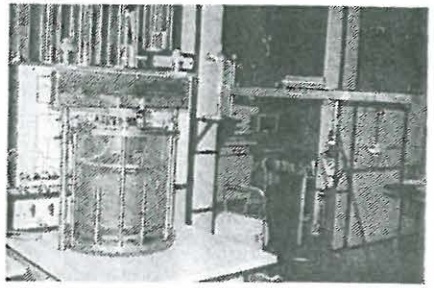

Fig. 26 Large scale triaxial set-up at AAU (250 mm H=D specimens)

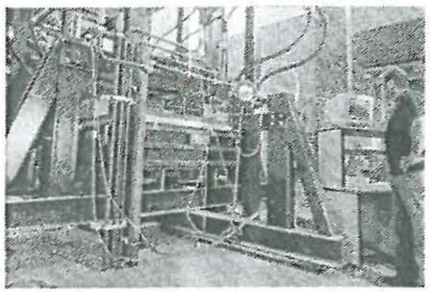

Fig. 27 Dynamic model set-up at AAU

As examples we now have access to:

Laboratory tests

- Resonant column (cf. Figure 25) or wave propagation tests, using bender elements in triaxial test set-ups, providing dynamic parameters at small strains (up to 10^{-4})
- Cyclic load-deformation tests, i.e. triaxial tests (cf. Figure 26), simple shear tests, torsional shear tests providing medium to large strain parameters
- Model test set-ups (cf. Figure 27). These support truly dynamic testing and allow studies of mechanisms and serve as verification tools for element testing at relevant strain levels.

Field tests

- Geophysical borehole logging tools
- Seismic surveying equipment for profiling on land as well as on water
- Surface wave techniques for profiling of elastic parameters
- Static insitu tests combined with seismic actuators and sensors (f.inst. CPT with seismic cone).

7. INTERPLAY WITH OTHER GEODISCIPLINES

In the pursuit of solutions using the geodynamic approach it is important not to loose sight of the other geodisciplines.

- Geostatics serve as an important link to "well-winnowed experience" of traditional design
- Geology and Engineering geology are prerequisites in order to establish and understand geological models and serve as a guide to proper application of test results
- Geophysics allow us to draw on matured methodologies, solutions and measuring and interpretation techniques.

We have to respect the geological setting which may pose challenges, advantages or dire problems. This depends on our ability to understand, respect and harness the powerful forces of Mother Nature (cf. Figures 28, 29).

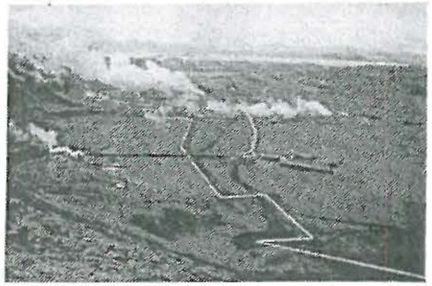

Fig. 28 Utilisation of the geological setting of Iceland. Nesjavellir geothermal powerplant near historic Thingvellir

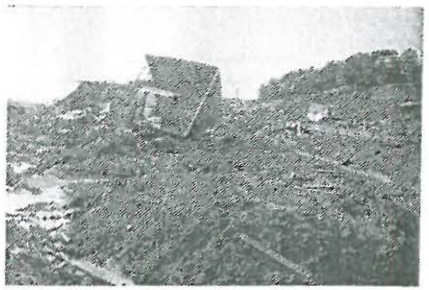

Fig. 29 The dire result of the presence of quick clay, Tuve Sweden.

8. POSSIBILITIES?

In conclusion the problems associated with the geodynamic approach are vastly outweighed by the possibilities offered.

The reasons are that

- modern laboratory and field testing equipment show great promise in quantification of dynamic properties of soils
- the numerical tools are maturing for handling dynamic aspects of both loading and resistance under 3D conditions

However, at the same time it is important to realise that

- proper soil-structure interaction is a must as de-coupling of dynamics in the structure and the soil may lead to unsafe or uneconomical solutions.

We must try not to treat our profession in a hand-to-mouth fashion (cf. Figure 30) but pay due respect to the dynamic nature of our environment - without doing away with well proven sound procedures.

Geodynamics do present us with problems and challenges but we are rewarded with a suite of possibilities for better understanding of soil behaviour and improved design of our structures.

Fig. 30 A traditional Saudi Arabian supper using only the right hand and the mouth

9. ACKNOWLEDGEMENTS

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Furthermore, we appreciate the arduous efforts by the late Moust Jacobsen who was instrumental in placing emphasis on geodynamics at Aalborg University.

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