RENÉ VISSER AND JOOP VAN DER MEER

IMMEDIATE DISPLACEMENT OF THE SEABED DURING SUBSEA ROCK INSTALLATION (SRI)

ABSTRACT

The integrity of subsea pipelines can be endangered by large free-spans, upheaval buckling and physical impacts like fishing nets and anchors. This can be avoided by installing pre-lay rock supports and post-lay rock covers. During rock installation a number of effects take place, such as surface erosion, rock penetration and immediate settlement of the subsoil. These processes are called "immediate displacement" and have a direct impact on the volumes of rock required to provide sufficient support to the pipeline.

The immediate displacement of the subsoil, and therefore the need for extra volumes of rock, can be accurately determined as long as sufficient geotechnical information on the seabed characteristics is available. Van Oord dredging and marine contractors has extensive experience in installing subsea rock by using flexible fallpipe techniques.

The Ormen Lange and Tyrihans Projects in Norway and Penguin Project in the UK are recent examples of projects where the flexible fallpipe (FFP) technique was used. On the Ormen Lange Project it was used to a depth of 870 m.

INTRODUCTION

As part of offshore oil & gas field developments pipelines and/or umbilicals are installed on the seabed. These lines may have to be protected against physical forces or upheaval buckling by the installation of post-lay rock covers or pre-lay rock supports in order to mitigate large free-spans. During rock installation a number of effects take place, such as surface erosion, rock penetration and immediate settlement. These processes are called "immediate displacements" and have a direct impact on the volumes of rock required to provide sufficient support and/or protection to the pipeline. The required volume of rock depends, amongst other factors, on the immediate displacements of the seabed during rock installation. Accurate knowledge of this is of importance to ensure proper project management. Van Oord as an experienced contractor in subsea rock installation (SRI) works, has extensively studied the effects of immediate displacements of the seabed and the impact on required rock volumes.

Above: FFPV Nordnes is a large (24,000 tonne) Flexible Fall Pipe Vessel used for securing subsea rock during the installation of pipeline (courtesy of VO/Truls J. Løtvedt).

This article describes the applications of subsea rock installation and gives a brief history of how this method has been developed and optimised. Possible alternatives to subsea rock installation are summarised. The immediate displacement of the seabed during rock installation is elaborated, focussing on the processes that occur when installing supports by a Flexible Fall Pipe Vessel, and taking into account the different soil conditions that may be encountered.

APPLICATIONS OF SUBSEA ROCK INSTALLATION

Subsea rock installation is applied to support and/or protect an offshore pipeline. More specifically subsea rock installation is applied to provide:
- physical protection from external objects like anchors and fishing nets (Figure 1);
- axial locking and upheaval buckling mitigation to prevent lateral movement of the pipeline e.g. owing to temperature changes of the pipe (Figure 1);
- free-span mitigation of pipelines in undulating terrain (Figure 2); and
- safe and stable crossings of previously laid pipelines (Figure 3).

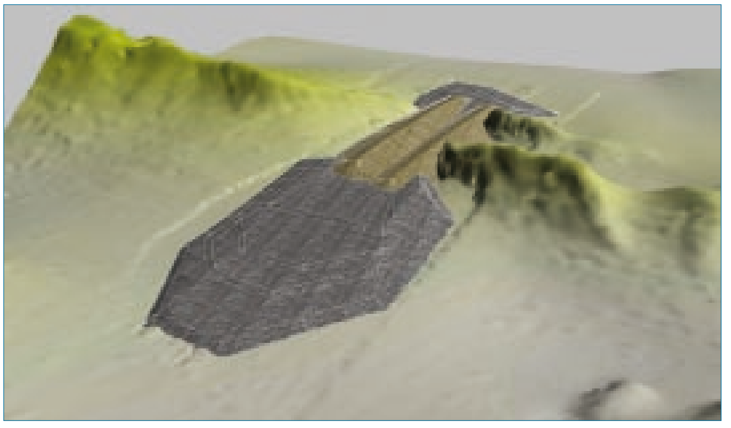

Figure 1. The basic design of supports (in brown) and counter fills (in green) for axial locking, preventing upheaval buckling and physical protection is basically identical (in green).

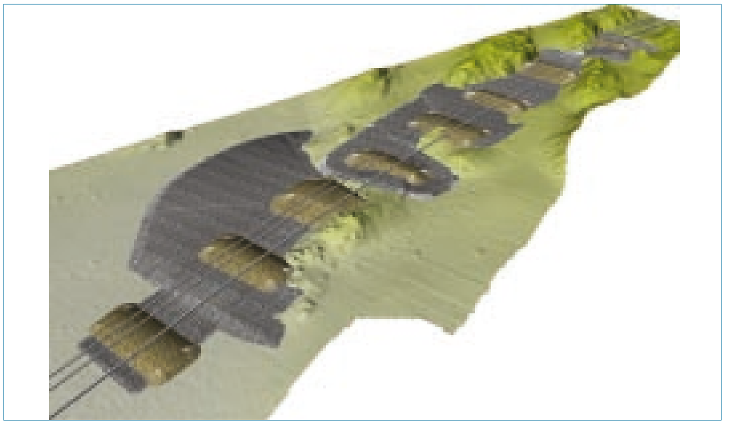

Figure 2. Free span mitigation supports (in green) including counterfills (in grey) for geotechnical stability.

Figure 3. A support for a pipeline crossing (in green) and counter-fills (in grey).

A BRIEF HISTORY OF SUBSEA ROCK INSTALLATION

Rock has been used for protection purposes for hundreds of years, e.g. for dikes and breakwaters. At first the installation of rock was done from ashore and from a vessel by hand (Figure 4). About fifty years ago the first automated rock dumping vessels were designed, built, tested and used for the massive Delta Works in The Netherlands. The rock was placed on deck and shoved over the side and fell through the water column to the designated location on the seabed. Nowadays this technique is still used and is referred to as side-stone dumping (Figure 5). With the increase of projects at greater water depths, the accuracy of rock placement was decreasing because of currents and dispersing of the rock. At this stage a new solution was developed entailing the use of a fallpipe in order to guide the rocks over a greater water depth (Figure 5). At the end of the 1970s a telescopic fallpipe was developed for rock installation at even greater water depths inducing large (drag and gravity) forces on the fallpipe.

In 1985 the *MV Trollnes* was equipped with a flexible fallpipe consisting of a string of bottomless buckets along two chains.
At the lower end of the string a remotely operated, self-propelled vehicle (ROV) was attached. This ROV secured more accurate placement of the rock amongst others by correcting the off-setting by currents.
The success of this technique has been proven during the past decades and resulted in the commissioning of two more Flexible Fall Pipe Vessels (FFPVs), the *Tertnes* (9,500 tonnes) (Figure 6) and the *Nordnes* (24,000 tonnes) (Figure 7). A new FFPV is under construction and will be operational in the first half of 2009.

ALTERNATIVES TO SRI

There are different alternatives to SRI for the physical protection and upheaval buckling mitigation of offshore pipelines. The most commonly used method is to apply a thicker armour layer or shell around the pipe, to cover it with concrete mattresses or to install the pipeline in a trench.

Instead of SRI for free-span mitigation, the pipe can also be supported with concrete elements or steel frames. Another option is to dredge the higher spots (applying the so-called pre-sweeping technique) to create a more even seabed, thus reducing the length of the free-spans. For a crossing with an existing pipeline, concrete mattresses may be used between the two pipes to avoid damage to both pipelines.

In general environmental conditions, the technical feasibility and cost aspects are considered after which eventually the most efficient and economic solution is chosen. Subsea rock installation is considered to be a competitive and reliable method to ensure the pipeline's integrity.

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Figure 4. Installation of rock was done from ashore and from a vessel by hand.

ENGINEERING

General

If subsea rock installation is required, the consultant assisting the operator and/or pipelaying company designs rock supports focussing on pipeline integrity and geotechnical stability of the subsoil at the location where the pipeline will be installed. The subsea rock installation contractor is then requested to perform the following actions:

1. review the design in order to optimise the installation efficiency
2. calculate the theoretical volume and the necessary practical tonnage of rock
3. check the geotechnical stability analysis (which is mostly done by an independent third party)
4. make project procedures and construction drawings for the FFPVs.

Review of the design is necessary as the Client will only give a so-called minimal design that fulfils the basic requirements for the pipeline integrity and the geotechnical stability.

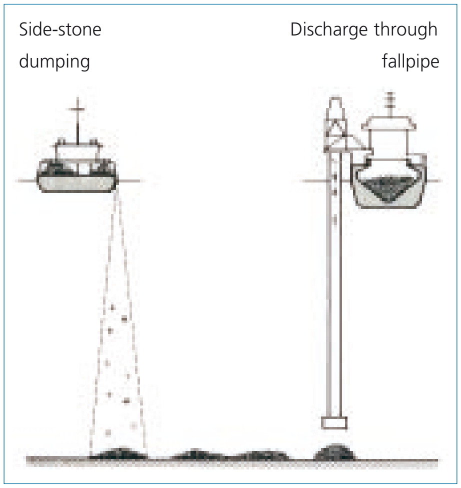

Figure 5. Schematic drawing of two methods of rock placement.

In some cases the installation efficiency can be improved by adaptations to the basic design, for instance, by installing counter fills with a sloping top surface instead of building up several terraces in a time-consuming operation.

Theoretical vs practical volume

The total required volume of rock for one support can be determined when the following items are taken into account:

- Theoretical rock volume required to install the support
- Installation losses during operations
- Immediate displacements of the seabed.

These items are graphically shown in Figure 8. The theoretical volume between the model and the original seabed can be calculated accurately using Digital Terrain Model (DTM) software. The installation losses depend on several aspects like sea state, currents, survey quality, water depth, support size, rock installation rate and experience of personnel onboard. Usually the losses can be determined based on expertise from previous projects. Immediate displacement will be described in detail below.

IMMEDIATE DISPLACEMENT

During rock installation a number of effects take place on the seabed. These processes are called immediate displacement.

The following phenomena have been recognised to contribute to immediate displacement:

- surface erosion;
- penetration of rock particles into the seabed and material flow into the rock skeleton;
- immediate deformations of the subsoil.

Each of the above-mentioned phenomena will be discussed below. The long-term settlements caused by drainage of subsoils under pressure and creep have not been considered in this article. A practical way of dealing with long-term settlements is to install the rock in two phases.

After installing approximately 80% of the final support height, the final 20% can be installed to the final design height when a period of 3 to 6 months for subsoil settlement has been allowed for.

Surface erosion

The seabed is generally covered by a thin weak top layer which can be detected by

Figure 6. The FFPV Tertnes worked on the recently completed Ormen Lange project.

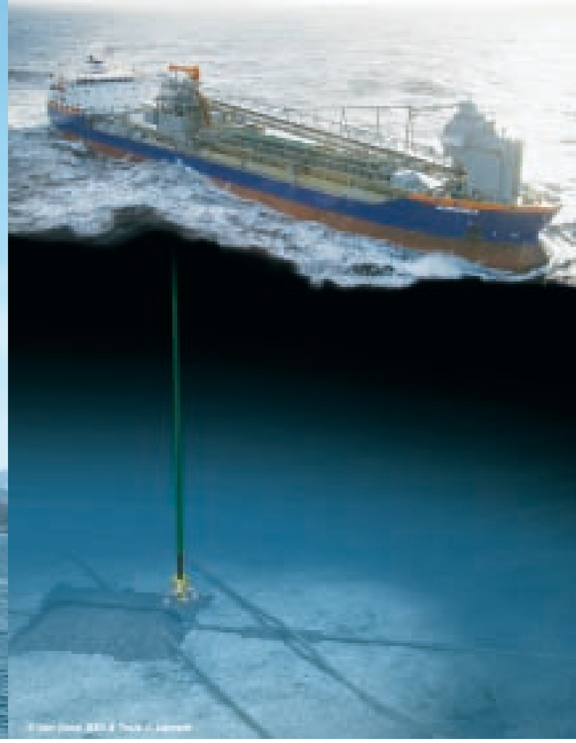

Figure 7. Artist's rendering of the FFPV Nordnes working on a pipeline crossing.

survey of the seabed with multi beam echo sounders. Cone Penetration Testing (CPT) is not sufficiently reliable to accurately assess the characteristics of this top layer. During subsea rock installation a mass flow is created within the fallpipe system. The velocity of this mass flow is in the order of 4 m/sec at the end of the fallpipe when it is located about 5 m above seabed. Owing to this mass flow a water overpressure occurs at the seabed, thus washing out the weak top layer and resulting in surface erosion. Depending on the available soil information an assessment of the surface erosion that may be expected can be made.

In general the erosion varies between 0 and 15 cm for hard clay or dense sand to soft clay with a water content equal to the liquid limit or very loose sand respectively.

Initial rock penetration into seabed

During the rock installation the individual particles will penetrate into the seabed. The penetration depth depends amongst others on the diameter of the stone, its velocity at impact, and the strength as well as the consistency of the subsoil.
The penetration depth is calculated by using the impulse balance:

$$F_{net} \cdot \Delta t = m \cdot \Delta v \quad \left(F_{net} = m \cdot a = m \cdot \frac{\Delta v}{\Delta t}\right) \qquad (1)$$

where

F_{net} = net force acting on the stone [N]

m = mass of the stone = $\rho_r \cdot \frac{1}{6} \pi (D_s)^3$ [kg]

Δt = time step [s]

Δv = variation in the velocity of the stone in a time step [m/s]

a = acceleration of the stone [m/s²]

The reduction of the velocity of the stone during each time step can be calculated using:

$$\Delta v = \frac{F_{net}(t)}{m} \Delta t \qquad (2)$$

The penetration finally stops when $v_{stone} = 0$, so the duration of the impact, t_{impact}, and the initial penetration, S_{init}, (see Figure 9) are given by (3) and (4):

$$v_{bot} = \int_{t=0}^{t=t_{impact}} \Delta v(t)dt = 0 \qquad (3)$$

$$s_{init} = \int_{t=0}^{t=t_{impact}} v(t)dt \qquad (4)$$

where:

v_{bot} = stone velocity just above seabed

To solve equation (2), the resultant force acting on the stone, F_{net}, has to be determined for every t.

$$F_{net}(t) = F_{gravity}(t) - F_{archimedes}(t) - F_{drag}(t) - F_{bearing}(t) \qquad (5)$$

where:

$F_{gravity}(t)$ = gravity force on the stone

$F_{archimedes}(t)$ = buoyancy force (as defined by Archimedes)

F_{drag} = drag force by the water on the stone

$F_{bearing}$ = force by the soil acting on the stone as given by Brich-Hansen [1].

The main results of penetration depths calculated for a number of different clay strengths and loose sand when using rock with a diameter of 1 to 5 inch are summarised in Table I.

There is no proven formula available to calculate the penetration of a falling stone into the seabed. Due to the lack of such a formula, alternative calculation methods have been studied. Calculations based on the bearing capacity formula, which is originally meant to analyse an equilibrium condition only, appear to provide realistic results for the analysis of a failing mechanism as well.

Additional penetration by material flow into the rock skeleton

After the occurrence of the initial penetration, contact stresses at the rock-subsoil interface are increasing during further build-up of the structure. Initially and for small additional loads this interface is stable. When higher contact stresses

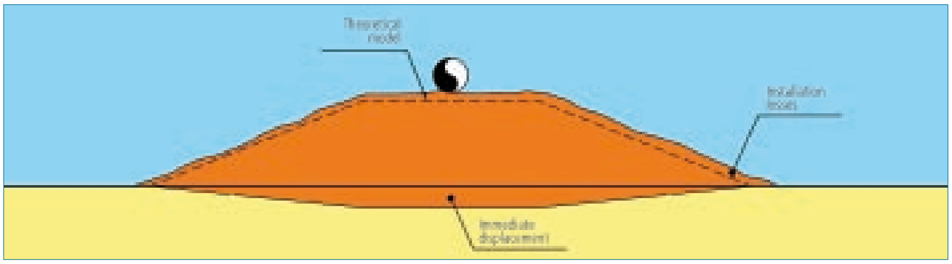

Figure 8. The total required volume of rock for one support can be determined when the theoretical rock volume required to install the support, the installation losses during operations and the immediate displacements of the seabed are considered.

between subsoil and rock fill occur, the rock will penetrate further into the subsoil until a new equilibrium is obtained.
This mechanism is graphically shown in Figure 9. The additional penetration D can be estimated by using a reological model. The pressure loss over zone D can be estimated by using the following formula:

$$p = S_u * \sqrt{(n / \kappa)} * \alpha * D$$

where:

p = pressure [Pa]
S_u = remoulded undrained shear strength [Pa]
n = porosity [-]
κ = intrinsic permeability [m^2] the best estimate for D_{15} = 0.04 m and n= 0.4 is $\kappa = 2*10^{-6}$ m^2
α = constant in the range 0.6 to 0.9 with a best estimate of 0.75 [-]
D = additional penetration [m]

Based on the above method a graphical representation of the results of the calculations for different undrained shear strengths and support heights is given in Figure 10. The results show that the material flow into the rock skeleton is rather limited. Only when installing higher supports on very soft clays can an effect caused by material flow into the rock skeleton be expected. Since the rock particles squeeze the clay during the installation process, it is realistic to consider the remoulded undrained shear strength.

Immediate deformations subsoil

Owing to the weight of the support structure immediate deformations can be expected in sand as well as in clay. The occurrence of immediate deformations depends on several aspects.

Compressibility subsoil
The compressibility of sand is normally small. The settlement is calculated considering drained characteristics of the material. Although only small displacements occur in sand, they still contribute to the immediate settlements to be accounted for.

The immediate deformations of clay can be calculated using the effective strength characteristics (φ', c') and deformation parameters (oedometer modulus M) while allowing for the development of excess pore pressures simulating undrained behaviour. In this way the immediate deformation for every support can be calculated.

Layer thickness
The thickness of especially clay layers governs the magnitude of the immediate deformation. The greater the thickness of the layer, the larger the settlement. Owing to the fact that clay layers intermediate with sand layers, some consolidation settlement during the rock installation should be taken into account.

Geometry support structure
The geometry of the support structure determines the loading on the seabed. A higher support results in a higher loading, thus causing larger deformations in the subsoil. An increase in length and/or a width of the structure will further result in an increase of the stress at deeper levels in the subsoil, thus resulting in a higher level of immediate deformations.

Calculation method
A 2-dimensional finite element analysis should be used since vertical displacements are introduced by horizontal deformations. This is caused by the fact that, in principle, no volumetric change occurs during undrained loading conditions in clay. This principle is graphically represented in Figure 11 which shows a deformation pattern obtained with the finite element software Plaxis. Immediate deformations as a function of the support height and clay layer thickness are presented in Figure 12. The immediate deformations in sand with a deformation modulus of 10 MPa are in the range of 0 to 2 cm for supports of maximum 5 m height on sand layers of 3 m thick.

CONCLUSIONS

Immediate displacements during subsea rock installation can be accurately assessed as long as sufficient and reliable soil information is available.
The immediate displacement can be divided into four phenomena:
1 surface erosion,
2 penetration of rock particles into the seabed,
3 material flow into the rock skeleton and
4 immediate deformation of the subsoil.

The surface erosion varies generally between 0 and 15 cm for hard clay or dense sand to very soft clay or loose sand, respectively. The initial penetration of rock particles into the seabed and the material flow into the rock skeleton mainly depends

Table I. Penetration S_{init} in seabed

	remoulded undrained shear strength S_u in kN/m².			sand
	S_u = 1	S_u = 5.0	S_u = 15	Loose
S_{init} in cm	21	6	3	9

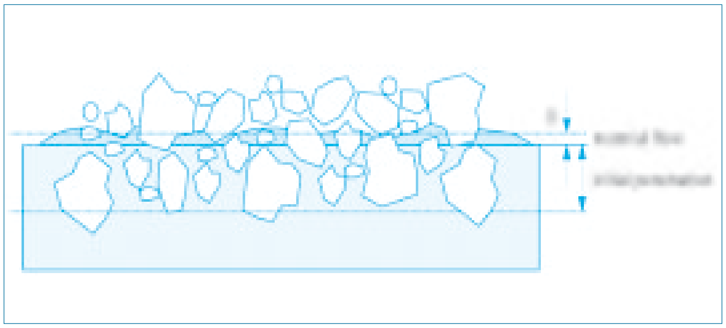

Figure 9.
Rock penetration.

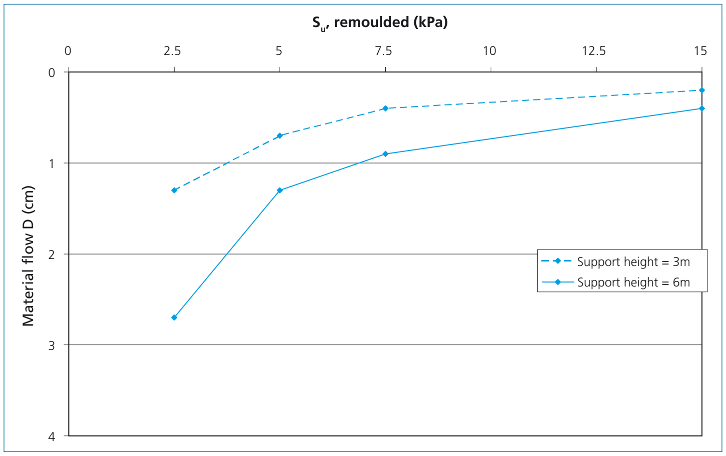

Figure 10.
Material flow D as a function of remoulded undrained shear strength S_u and support height.

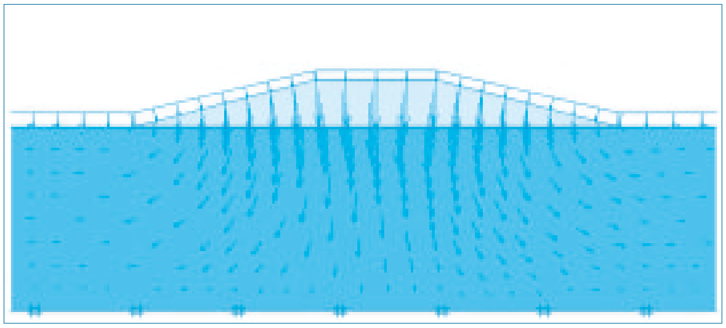

Figure 11.
Deformation pattern in finite element software.

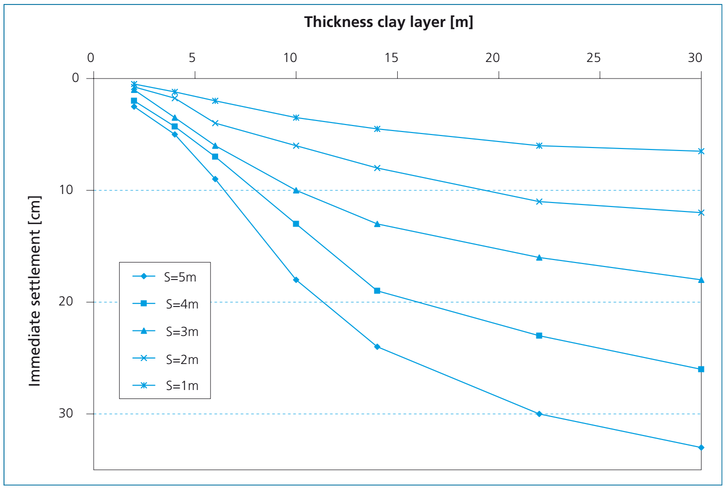

Figure 12. Immediate deformations in clay for deformation modulus M = 2MPa. Each line represents a different support height S.

on the support height and the remoulded undrained shear strength of clay or the internal friction angle of sand. This results in a penetration of 0 to 20 cm in practice.

The immediate deformation of the seabed owing to the static weight of the supports is calculated by means of a finite element programme. For sand the deformation modulus in combination with effective soil parameters is used. For clay the oedometer modulus M and effective strength parameters in combination with undrained behaviour (allowing for the development of excess pore pressures) is adopted. In practice the immediate deformation ranges from 0 to 25 cm depending on the support height and the consistency of the subsoil. The following recommendations should be considered when assessing the immediate displacements:

- The information on the strength and consistency of the first 0.5 m thick top layer is considered not to be reliable if only CPTs results are available.
- A remoulding effect of 50% is considered in the analysis regarding the penetration of the individual particles and the material flow into the rock skeleton. In sensitive clays a higher reduction in strength may be expected.

The effects caused by long-term settlement can be addressed by installing rock supports in two phases with a 3 to 6 months settlement period in between.

As a result of evaluating several projects the conclusion can be made that the difference between the estimated volume of rock, including immediate displacement, and the actual installed volume is only 2 to 3%. This shows that the effects of immediate displacements can be calculated accurately by using the methods described here, provided that the knowledge of the subsoil characteristics is sufficient.

REFERENCES

Brich-Hansen, "A revised and extended formula for bearing capacity". *Bulletin 28,* The Danish Geotechnical Institute, 1970.