[PROC. OF JSCE No.388/III-8 (Geotechnical Eng.) December 1987]

Invited Paper

THE FORMATION OF POCKMARKS AND THEIR POTENTIAL INFLUENCE ON OFFSHORE CONSTRUCTION

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ABSTRACT

Pockmarks are craters formed in the soft seabed by gas and in some cases liquid expulsion. They were first described on the Scotian Shelf in 1970 (King and MacLean, 1970) and have since been mapped in a range of shallow seas including the North Sea and the Arabian Gulf. Pockmarks range in size from less than one metre to about 200 m across and up to 20 m deep.

There are assumed to be three phases of pockmark development :

1) The pressure build-up phase, whereby gas accumulates and builds up local pressure below the seabed.
2) The eruption phase, where by gas, liquids and solids are ejected into the water colum, and
3) The post eruption phase, which can either be a dormant phase or one where gas is continually seeping through the pockmark floor.

Triggering of pockmark eruptions are discussed. They may be triggered by earthquakes or seabed pressure perturbations caused by tidal or gravity waves or, in deep water, by a combination of tidal waves and low atmospheric pressure and storm waves.

Pockmarks are of concern in relation to seabed construction.

Pockmark avoidance and crossing with pipelines is discussed together with methods of artificial gas drainage away from construction sites.

1. INTRODUCTION

Craters in the soft seabed termed pockmarks, have been known since 1970 and have been found to exist worldwide in waterdepths ranging from 30 m to over 3 000 m (King and Maclean, 1983; Hovland and Judd, in press). Pockmarks range in size from less than 1 to 200 m across and from 0.5 to 20 m in depth. They normally occur where the seabed consists of soft silty clay, and they are assumed to be the result of gases

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Keywords : *pockmarks, gas seepage, triggering mechanism, offshore construction*

Profile

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and liquids passing through the seabed, as will be discussed later.

The influence of pockmarks on offshore installations and construction has previously been evaluated by several authors. Newton and co-workers (1980) concluded their evaluation of pockmarks vs engineering hazards as follows : "Pockmarked areas in the sea floor are likely the result of gas or water venting from the shallow or deep subsurface. Until their origin and the possibility of reactivation can be accurately defined, pockmarked areas must be considered a geologic hazard requiring special design considerations". (Newton et al., 1980, p. 429).

Judd (1981) saw the greatest hazard to offshore structures in the size and shape of pockmarks and their potential growth during the lifespan of the structure. He also mentions that there may be a danger of intermittent low pressure gas escape beneath structures in pockmarked or gas-charged areas.

Green and co-workers (1985) addressed the pockmarks vs. structures at the giant Troll gas field in the Norwegian Trench.

Their conclusions were :

"The base (worst) case assumed is that pockmarks may create risks for :

a) short-term settlement of a gravity-based production platform;
b) spanning of pipelines
c) long-term risks (a) and (b) above due to growth of new or enlarged existing pockmarks.

Owing to the uncertainty of numbers, sizes and location of future pockmarks generated within the Troll field development area, it is appropriate that engineers should express pockmark risk in terms of "return periods", just as design environmental forces are" (Green et al., 1985, p. 119).

2. FORMATION MODE

After many years of carelul study and review of a considerable amount of worldwide data it has recently been possible to state a mechanism by which these enigmatic features are formed (Hovland and Judd, in press). The formation theory is based on extensive geophysical surveying, detailed visual inspection of a few pockmarks in the North Sea, including an active one, and on geological and geochemical seabed sampling. The main conclusion is that pockmarks are formed by gas eruption and seepage through the seabed, although in a few case interstitial water is assumed to have been the active agent. Since pockmarks are mostly found in areas of pertroleum generation and accumulation and since the geochemical sampling both of seeping gas and of sediments shows relatively high concentrations of methane, the gases responsible for the pockmarks are assumed to be mainly petroleum-related. Actively seeping pockmarks have so far been surveyed in the Gulf of Arabia (Ellis and McGuinness, 1986) and in the North Sea (Hovland and Sommervill, 1985). Pockmarks are geologically unique geomorphic features since they have neither been found on the land surface nor in the lithified geological record. They were therefore unknown until described by King and MacLean in 1970, after a sidescan sonar survey off the coast of Nova Scotia.

In order to understand the formation mode of pockmarks we have to know the hydraulic properties of the sub seabed. However, very little is known about sub seabed hydraulics and hydrology. Detailed hydraulic data from the seabed are notoriously difficult and expensive to acquire, so the tentative formation theory for pockmarks are based upon a series of assumption.

Firstly it is assumed that gases generated at depth migrate through thick layers of subsurface rock and sediments. These assumptions are quite realistic in provinces of deep oil and gas generation. The abundance of gas sampled at surface is methane, which is highly mobile and of low molecular weight. Any fissures and porous volumes in sediments therefore act as migration paths and reservoirs for the gas. Secondly it is assumed that the gas accumulates in porous layers below the upper soft, silty clay layer which is water-saturated and has low permeability. The low permeability of this upper barrier is assumed to be the reason why gas is "focused" and erupts at singular points in the seabed. The actual point of eruption is thus assumed to be governed either by the presence of a shallow gas reservoir (lying just below

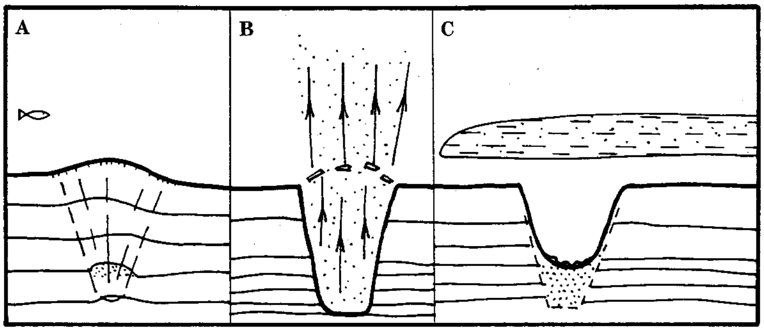


Fig. 1 Formation model for pockmarks
A) Pressure build-up, B) Eruption phase, and C) Post eruption phase. (from Hovland and Judd, in press).

the upper layer) or by points of weakness (faults/fissures) in the soft silty clay layer. On these assumptions the following phases are assumed to take place when pockmarks are formed (see Fig. 1, Hovland and Judd, in press) :

(1) Interstitial gas builds up pressure in a shallow gas reservoir either within the upper soft, silty clay layer or immediately below it. This may lead to a slight doming of the seabed (actually observed on several occasions).

(2) The soil structure in this dome is then assumed to fail due to sudden overstressing, triggered by some sort of mechamism to be discussed later. The overstressing of the dome causes a network of fractures and faults to develop on it.

(3) The assumed sudden drop in pressure, caused by these fractures, induces the gas to flow freely out of the dome. This initial flow is probably quite violent and could be accompanied by interstitial liquids and solid particles. The sediments thus mobilized are assumed to be thrown up into the seawater column where the finest grains are suspended and dispersed by currents. The depression formed by this mass transport is assumed to be a "fresh" pockmark, characterised by a group of densely clustered "unit pockmarks" (Hovland et al., 1984). The unit pockmarks are up to 2 m wide and less than 1 m deep and are assumed to appear where a single jet or bubble-stream occurred through a fractrue segment.

(4) The newly formed pockmark now represents a point of weakness in the upper low-permeable layer. It should therefore subsequently act as a natural gas drainage vent for further migrating gas. If no subsequent continuous seepage or micro-seepage of gas occurs then the pockmark is assumed to erupt again when pressure builds up, but with much less violence than on the initial occasion.

3. GASES STORED IN SOFT SEDIMENTS

During high resolution shallow seismic surveying it is quite common to find areas with suspected gas in the upper sediments (Jones et al., 1986; Stefanon, 1980; Tinkle et al., 1973; Hulbert et al., 1981). Acoustically detected gas-charged sediments have also been documented geochemically (Nelson et al., 1979; Hovland and Sommerville, 1985; Hovland et al., 1987).

Much of the interstitial gas found at shallow sediment depths in marine, soft sediments seems to consist of methane. It is assumed that the gas was produced somewhere below the storage layer, either biogenically, in relatively shallow sediments (<1 000 m) or thermogenically in deep-lying source rocks. Since the acoustically detected gas-charged sediments often form a sharp upper boundary it is assumed that this boundary represents transition to a less permeable or an "impermeable" layer. In the following the acoustic boundary will be called a "gas front" (see Figs. 2 and 3).

Normally, soft, marine sediments consisting of silty clay or silty, sandy clay are saturated with water and often have a water content over 50 %. Their effective porosity is of the same order. For a "gas front"

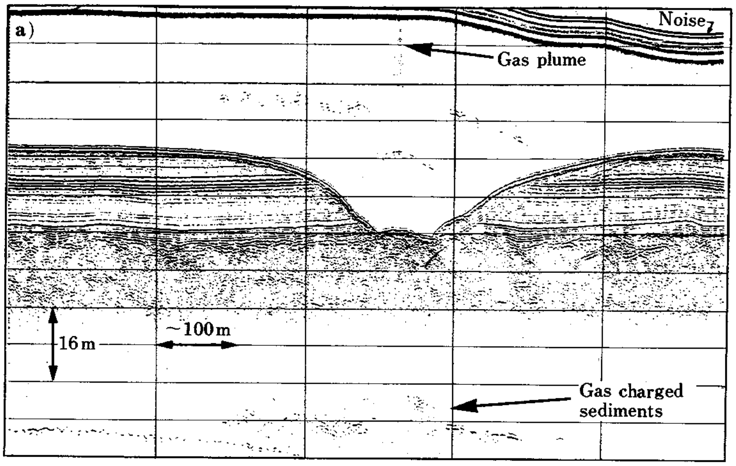


Fig. 2 An active pockmark in the North Sea.

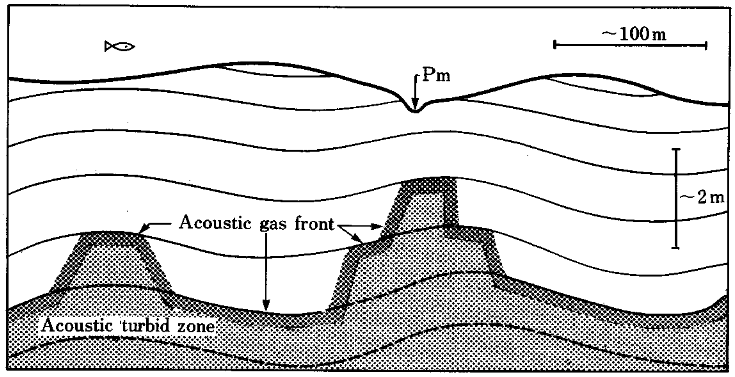


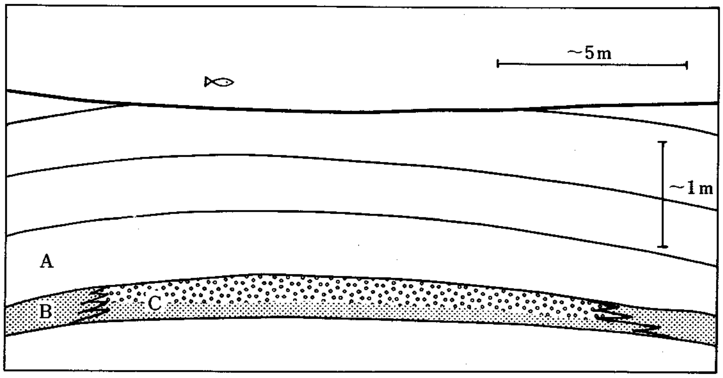
Fig. 3 An "upper gas-front" develops where migrating gas is hindered verically by impermeable fine-grained, water-saturated, cohesive sediment layers.

to form the following process is assumed to occur in these sediments : gas (methane) -molecules diffuse or migrate upwards, transmitted in the pore water system.

The gas may also be transmitted by direct pore water flow or by bubble transport in permeable layers or through fissures and fractures. No matter how the gas molecules are transmitted, the fact remains that the pore water in shallow sediment depth often becomes saturated with gas. Upon gas saturation micro-bubbles form interstitially. These will respond to buoyancy and seek the upper portion of a permeable layer (Fig. 4). The bubbles will thus eventually take over the void space previously occupied by pore water and therefore tend to increase the local interstitial pore water pressure.

The "gas front" is often found to cut across sedimentary beds, as shown diagrammatically in Fig. 3 (Hovland, 1983). If the migration and diffusion of gas continues from below, it is self-evident that the gas pressure in the upper sediments, sooner or later, will expel enough interstitial pore fluid and build up enough pressure for the overburden material to fail mechanically. Howerver, it is most likely that minute pressure fluctuations will occur and speed up the time to failure. The conclusion is therefore that even if we treat layers as impermeable, they will eventually break and become locally "permeable" upon over-pressuring.

Since pockmarks are common features on the modern soft seafloor, there is a likelyhood that many of them will show some sort of activity over a short time span (for example a 10-year period). Very few pockmarks have been found to be continuously active and seeping gas. However, a number of them seem



A = "Impermeable" layer
B = Permeable layer
C = Gas saturated permeable layer

Fig. 4 Gas stored in a very shallow "reservoir".

quite "fresh" when surveyed with high resolution side-scan sonar. The main remaining uncertainty with respect to pockarks and their possible influence on structures is their return period (Green et al., 1985). In other words what makes them active and for how long are they active, or for how long will they remain dormant. Before continuous measurements have been made inside or near pockmarks which are or suspected to be intermittently active these answers connot be given. However, there are certain indications that some pockmarks erupt during stormy weather and that low pressure or a high seastate activates gas expulsion (McQuillin and Fannin, 1979; Hovland and Judd, in press). In theory only very weak cyclic pressure forces are needed to pump gas bubbles through soft, unconsolidated seabed sediments. Each time the pressure is reduced the small gas bubbles are assumed to expand and rise to a higher level within the sediments. This is due to buyoancy forces which act much stronger on the gas bubbles than on the surrounding water and solid sediment matrix. The stored gas would thus represent a potential sub seabed energy pool, ready to be set free when cyclic loading occurred. The first severe autumn or winter storm, following after a prolonged calm period, would thus probably provide the necessary triggering event for intermittently erupting pockmarks.

Madsen (1978) and Yamamoto et al. (1978) obtained analytical solutions to the problem of wave-induced pore pressures and stresses in a poro-elastic seabed. They employed Biot's consolidation equations and arrived at a rather complex final governing linear differential equation of the sixth order. Howerver, Okusa (1985) managed to reduce the governing equation to a linear differential equation of the fourth order, where the physical meaning of the solutions could better be understood. Okusa used the conventional assumptions employed in Biot's theory (Biot, 1941) with the following additions:

(1) the water and gas phase within the sediment is considered as a single compressible fluid

(2) the effects of gas diffusion through pore water and the movement of water vapour are ignored

(3) the effetive stress principle is unchanged from the normal definition for saturated soils (Okusa, 1985).

The general solutions for a homogeneous poro-elastic sediment contain the wave-length, the wave period, sediment permeability, two elastic constants for the sediment, and Skempton's pore pressure coefficient, B (Skempton, 1954). When cyclic pressure, with a load increment, p, is applied to a gas laden sediment, the load is divided into the effective stress, p' and the pore pressure, u, (Okusa, 1986). Skempton's pore pressure coefficient, B, here plays an essential role. It is defined as follows:

$$B=1/(1+n\beta/\alpha)$$

where n is the porosity of the sediment, β is the compressibility of the pore fluid, and α is the compressibility of the porous skeleton. For a totally water saturated sediment, $B=1$. The terms which

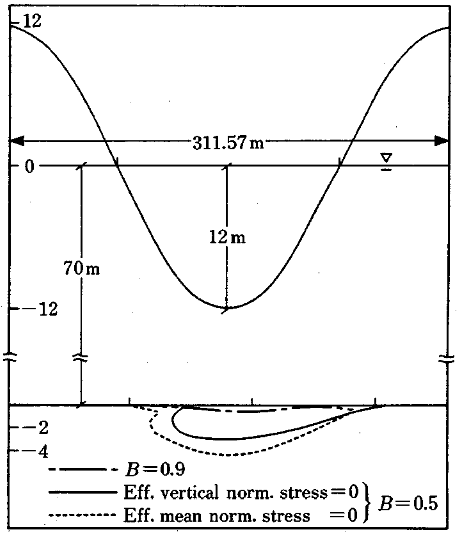


Fig. 5 Cyclic "pumping" of the seabed by gravity waves (from Okusa, 1985).

concern permeability, elastic constants and wave characteristics in the solutions of the governing equations then diminish, and the solutions only depend on wave-length and wave height.

Skempton's pore pressure coefficient, B, however, rapidly decreases from 1.0, even with very small amounts of gas in the sediment. Okusa (1985) thus found that low values of B are more likely to produce unstable conditions under the trough of a wave, where the effective stresses induced by wave action are of negative sign (see Fig. 5, from Okusa, 1985). Some of Okusa's results proved to be directly applicable to the problem of pockmark development : "Under certain wave conditions, gas-laden submarine sediments can be liquefied under the trough of the wave owing to the wave-induced negative effective stresses added on the stress state at rest. The wave-induced liquefaction progagates in the direction of the wave. The smaller the value B, the deeper the wave-induced liquefaction is. For a sandy sediment with $B=0.5$, the wave-induced liquefaction may reach a depth of the order of the wave amplitude under certain wave and soil conditions" (Okusa, 1985, p. 530).

It may thus be concluded that cyclic loading of the seabed may lead to loacal liquefaction (doming and "fracturing") when the seabed is soft (poro-elastic) and contains a varying amount of gas.

One possible flaw in this way of reasoning is that pockmaks also occur in water depths of over 200 m, where the influence of surface ocean waves is not expected to be significant.

The cyclig pressure effect on the seabed is, however, expected to diminish rapidly and become negligible in water depths increasing upwards from 150 m. The reason for this is mainly the frequency damping effects even for large surface (storm) gravity waves.

But there are other conceivable low frequency, cyclic pressure forces which could possible provide the necessary pumping effect on a poro-elastic seabed in deep water (>200 m). There are the diurnal tidal waves, which combined with storm surges and extreme atmospheric pressure situations could possibly exert the necessary differential pressure on the seabed to induce interstitial gas movement. There are also the so-called infra-gravity waves, seiches and internal waves which may also provide pressure perturbations in deep water. Earth tremors caused by local earthquake would naturally provide enough disturbance in the soft sediments to induce gas movement. However, earthquake events are considered to be too rare in order to explain the freshness of some pockmarks, especially in the North Sea.

4. INFLUENCE ON OFFSHORE CONSTRUCTION

Since pockmarks may be or could become sites of natural gas venting they should be avoided when pipeline routes and platform sites are planned. If a pockmark cannot be avoided along pipeline routes its freshness and likelihood of future eruption should be assessed by looking for shallow seismic indication of local gas accumulations. If the "unavoidable" pockmark is not "fresh" and no gas anomalies are found nearby then there should be no danger in crossing it. The main problem is then reduced to one of free spanning and careful monitoring after laying.

There are several pipelines in the North Sea which have been routed through pockmark fields. A section of such a route is shown in Fig. 6 (from Lund and Gjertveit, 1985). Here the selected pipeline route is optimized to avoid pockmarks with the maximum pipe curve-radius possible. The section shown is from the Statpipe route between Kårstø on land and the Ekofisk field in the Norwegian sector of the North Sea. Along another section of the Statpipe route unexpected problems were encountered during laying. The route had to go through an unplanned narrow corridor which had been cleared for World War II mines (Lund and Gjertveit, 1985).

A planned deviation of the route therefore had to be abandoned which resulted in the crossing of a pockmark. This caused a 70 m wide span of maximum 6 m height (Lund and Gjertveit, 1985).

Fig. 7 shows how a trenching machine (Biberg and Årild, 1979) subsequently lowered the pipe up to 4 m into the shoulders of the pockmark, thereby reducing the span to an acceptable length and height. During the Statpipe project a total of 842 km pipeline was laid in the North Sea. A total length of 32 km was trenched successfully for span correction across iceberg ploughmarks, pockmarks and terrassic seabed forms (Lund and Gjertveit, 1985).

To date there is no record of platforms or other large seabed founded structures having been installed near pockmarks or in gas-charged seabed sediments.

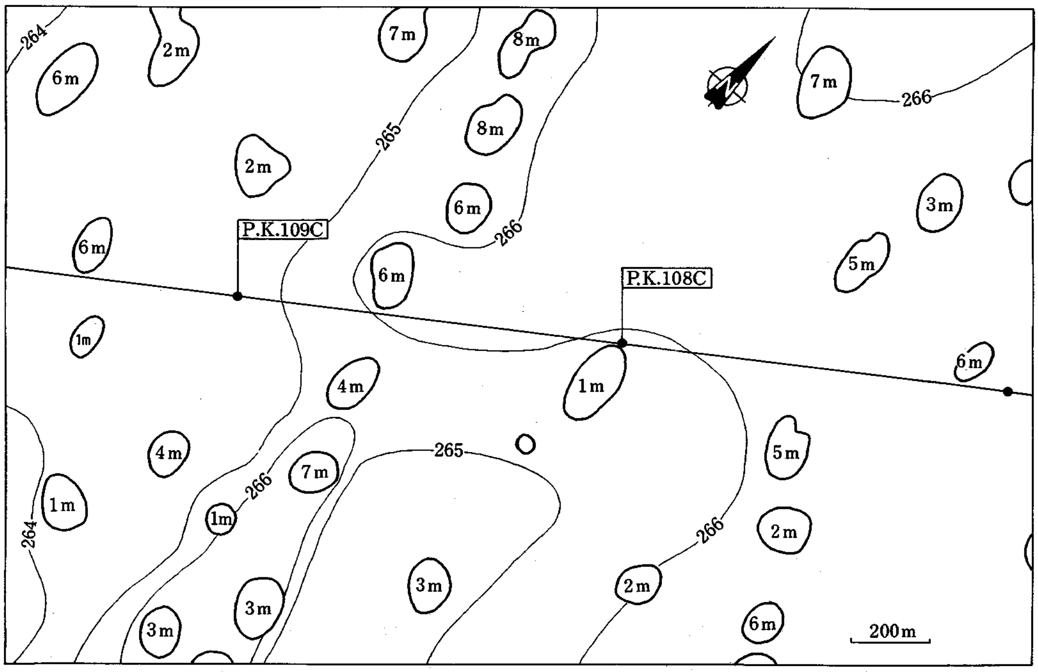


Fig. 6 Section of a pipeline route through a pockmark field in the Norwegian Trench. The maximum depth below mean seabed level (m) is given inside each pockmark P. K. =kilometre post along the route. (from Lund and Gjertveit, 1985).

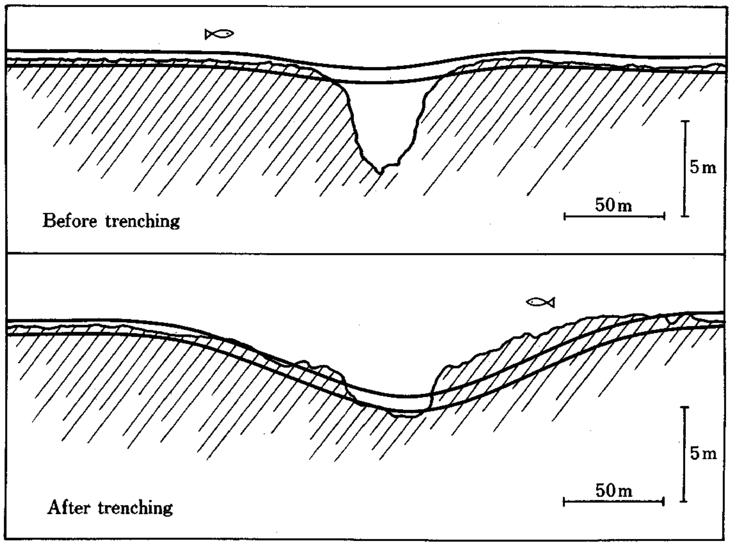


Fig. 7 The trenching of a pipeline into a dormant pockmark (From Lund and Gjertveit, 1985).

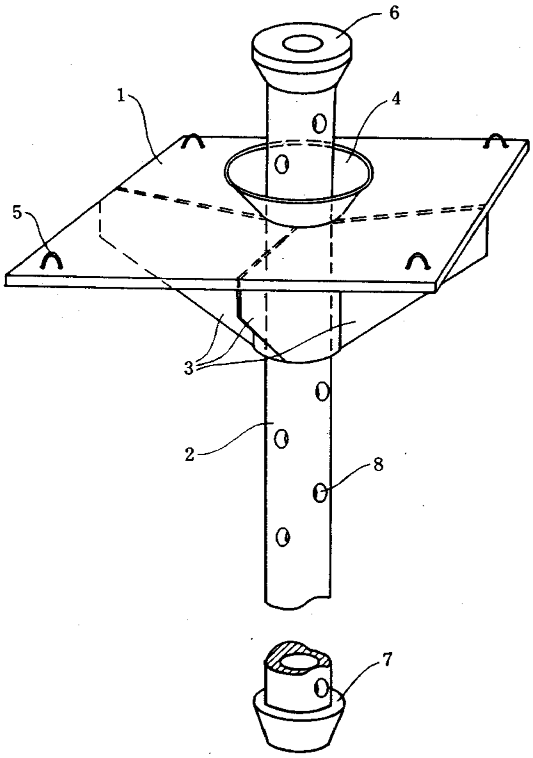


Fig. 8 A gas drainge pile. (From Gudmestad and Hovland, 1986).

Ellis and McGuinness (1986), however, report the following from the Arabian Gulf: "There is evidence that any activity, anchoring, rigs jacking up, or fish feeding, which disrupts bottom equilibrium can initiate pockmark activity. At one location a preconstruction survey showed no pockmarks. A post-construction survey done a year later found seven pockmarks, five of which were active".

Gudmestad and Hovland (1984) addressed the problem of what measures can be taken, prior to construction of heavy structures in pockmark-prone areas. Assuming that pockmarks form due to local gas or pore-water pressure build-up they described a method of seabed drainage of the construction site. This method is based on the assumption that gas below the so-called "upper gas-front" (Fig. 3) fovours lateral bed-parallel migration as opposed to vertical migration. In effect, this means that gas will accumulate below the "upper gas-front" until it is either prevented from moving laterally or is pumped upwards. This method for artificial seabed gas venting relies on the fact that the upper sediment layer is water-saturated, cohesive, and impermeable to normal gas migration. The method consists of penetrating the upper sediment layer with permanent, vertically-installed drainage piles (Fig. 8). The piles consists of perforated steel tubing which is supported by a baseplate on the seabed. Such piles penetrate the "upper gas-front" and should be spaced closely around the construction site to prevent large shallow gas accumulations from forming.

The existence of pockmarks and very shallow gas seems to be relatively common features which have to be dealt with by geotechnicians and geophysiscists as the demand for seabed construction move into deeper water where fine-grained, soft sediments are common. There are still many unanswered question as to how pockmarks develop and work. More field data are needed, especially from closely monitored subseabed pressure variations, before optimal methods or instructions can be designed on how to cope with these enigmatic seabed features which so far have not been found on land.

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(Received September 21 1987)