MARINE GEOTECHNOLOGY A NEW INTERDISCIPLINARY BRANCH OF SCIENCE AND TECHNOLOGY

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Abstract Marine geotechnology which has been developed through investigations and explorations of offshore oil and gas fields and other marine engineering activities is reviewed. After the scope of this interdisciplinary branch of science and technology is defined, the developments of marine geotechnology are historically sketched. The problems discussed in this paper are (1) characteristics of submarine sediments, (2) stability-instability of the seafloor, (3) wave-induced pore pressure in relation to the seafloor instability, (4) gas in submarine sediments in relation to stress conditions in sediments and the formation of pockmarks. The importance of geology in the development of marine geotechnology is emphasized.

Introduction

Worldwide ocean developments on continental shelves during the last decade and on further deep water seafloors in recent years initiated the birth of a relatively new discipline of engineering geology, marine geotechnology (RICHARDS & HARTEVELT, 1984). As well known, such geological and geomorphological processes as drifting, sedimentation, erosion, resedimentation, consolidation, diagenesis, submarine slope instabilities (slump, slide, creep, etc.), turbidity current, pockmarks, and so on occur on the seafloor. When human activities work upon the seafloor, it is necessary to assess (1) the distribution of sediments, (2) the geological history of sediments, (3) the present topography (relief) of sediments and its relation to geological and geomorphological processes at work, and (4) the influence of human activities on geological environments of the seafloor and on the initiation of new geological processes.

Human activities upon the seafloor involve installations of such structures as harbor faci-

lities, offshore platforms for oil and gas, causeways, submarine pipelines, cables, reservoirs, etc. and engineering activities such as coastal and submarine disaster prevention works, extraction of seafloor mineral resources and marine energy, dumping of waste material, etc.

In this paper marine geotechnology or submarine engineering geology is defined as a discipline studying geological factors affecting physical, mechanical, chemical, paleontological, acoustical properties of submarine sediments, and assessing and controlling the static and dynamic response of sediments to human activities. Therefore, the objectives of marine geotechnology are to clarify and identify

(1) regional and local processes and their types affecting the transportation of sediment particles, sedimentation, erosion, sediment instabilities, etc.,

(2) vertical and lateral variation of the processes,

(3) classification of sediments by the index properties,

(4) response of the sediment skeleton-pore fluid to external forces, especially rough waves and earthquake shocks,

(5) sediment stability-instability (slump, turbidity current, liquefaction, rapid sedimentation, faulting, diapir, etc.) and unstable areas under natural conditions,

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(6) stresses in excess of natural stresses due to installations of structures, mining, engineering activities, dumping, etc.,

(7) types and degrees of potential hazards induced by natural agents and human activities,

(8) environmental change, including the ecosystem in and around submarine sediments and adjacent areas induced by human activities,

(9) static and dynamic response of the sediment-structure system due to natural forces, especially rough waves and earthquakes.

The most important environmental difference between submarine and subaerial sediments is that the former is under the influence of the seawater with a density 800 times higher than that of air. The seawater also contains various types of electrolytes. The existence of seawater not only affects the properties of submarine sediments, but also puts technological and economical constraints on human activities on submarine sediments.

Seawater is closely related to the sedimentary patterns, the formation of thick underconsolidated sediments in areas of rapid sedimentation, and the formation of overconsolidated sediments due to water erosion. The repeated loading by waves may affect the properties of submarine sediments. The existence of gases in submarine sediments changes their properties and the response to external forces. The electrolytes in the pore fluid have an important bearing upon the sedimentary structure of clayey soils.

To understand the physical, mechanical and chemical properties of submarine sediments formed under the influence of marine conditions, cooperation is essential among scientists and engineers in the fields of geology, geomorphology, geophysics, soil mechanics, civil engineering, oceanography, and ecology. In fact marine geotechnology is one of the new interdisciplinary branches of science and technology.

In this paper the author reviews the historical development and the state-of-the-art research in marine geotechnology and discusses some problems involved. He could not

refer to the problems associated with submarine survey and sampling. New techniques for submarine soil survey have been developed and are being innovated in recent years (RICHARDS & CHANEY, 1980; Japanese Society of Soil Mechanics and Foundation Engineering, 1982; RICHARDS, 1985; RICHARDS & ZUIDBERG, 1985a, b; de RUITER & RICHARDS, 1983; SEKO, *et al.*, 1985; ZUIDBERG *et al.*, 1985). The side scan sonar is one of the most promising tools for submarine soil survey (PRIOR & COLEMAN, 1980; RYAN, 1980; BELDERSON, 1985). Submarine soil sampling involves various problems of stress release and gas segregation by taking-up samples, in situ high water pressure, and so on. Those readers who are interested in submarine soil sampling problems can refer to the references (D'APPOLONIA, 1971; OKUMURA, 1974; ESRIG & KIRBY, 1977; OKUSA, 1978).

Historical sketch

The first paper systematically discussing submarine sediments in relation to submarine slope stability was published by TERZAGHI (1957). He classified the submarine slope instabilities in three categories: a) local, minor slumps on steep slopes (27—30°) on accumulated fine-grained silty material resting on coarse-grained material, b) large-scale movements of short duration on steep as well as on very gentle slopes of fine-grained cohesionless or slightly cohesive sediments (liquefaction failures), and c) more or less continuous slumping on gentle slopes underlain by soft, underconsolidated recently deposited clay. TERZAGHI explained the mechanisms of these slope failures on the basis of the principles of soil mechanics developed by himself and showed excellent examples.

The first step on marine geotechnology is assumed to have started with the discovery of an oil field in Lake Maracaibo, a brackish lake (the deepest water 250 m), Venezuela, in 1914 (BJERRUM, 1973). The surface geology of the lake floor consists to considerable depths of more than 70 m of soft clay with embedded layers of sand. Thanks to the development of new techniques for construction of offshore

platforms including techniques for subaqueous geotechnical survey, the oil extraction activity was expanded into deeper and deeper waters. Precast reinforced concrete piles of 50—70 m were used as foundations for the platforms. TERZAGHI was engaged in the consulting work for the platform construction and the landsubsidence associated with oil extraction.

In the Mississippi Delta area, where typical underconsolidated fine-grained material develops as TERZAGHI (1957) pointed out, an accident occurred to the towers which were built for the US Air Force in the years 1955—1956. After this failure an important step forward was taken in the 1960's when oil drilling and related installations of pipelines in the waters up to 60 m off the Mississippi Delta were implemented. The delta consists of highly plastic and very soft underconsolidated clay to depths exceeding 150 m, and various types of instabilities are observed here. The Mississippi Delta area often suffers from very strong hurricanes with wave heights in excess of 17 m (BEA, 1975). Boring platforms off the Mississippi Delta are of the jacket or template type which is supported by a long open-ended steel pipe pile foundation.

In the late 1960's the first commercial oil field, the Ekofisk field, was discovered in the Norwegian part of the North Sea, and after that new fields were discovered one after another in the British and Norwegian regions. Therefore, the North Sea region became one of the centers of the development of marine geotechnology together with the the Mississippi Delta region. The North Sea fields are located on the continental shelf of water depths of 70—100 m. This region was covered with the continental glacier in the Würm Age due to the lowering of the sea level and the advancement of the glacier. The soil conditions have been influenced by the fluctuations of the sea level, the advance and retreat of the glacier, and probably recent high waves. The North Sea is famous for its frequent and sudden storms where 100 year wave height is estimated to be over 27 m. The surface geology of the North Sea fields consists of a se-

quence of fine to coarse, dense sand and hard overconsolidated clay. "Taking into consideration that some of structures in the North Sea are of unprecedented dimensions and that most of the problems encountered are of a type which has never been tackled before, it is easily understood that the work with these structures has been exciting challenge" (BJERRUM, 1973).

Under these circumstances many great researchers from geology and soil mechanics have taken part in this new horizon of interdisciplinary collaboration between science and technology. In 1967 the first worldwide conference on marine geotechnology was held in Illinois, U.S.A., under the leadership of Adrian F. RICHARDS and its proceedings (RICHARDS, 1967) were a milestone in the development of marine geotechnology. In the 1970's a couple of state-of-the-art reports and textbooks on marine geotechnology appeared reflecting the progress made in the ocean development. In 1973 BJERRUM (1973) reviewed geotechnical information relevant to the design of offshore structures of the oil and gas fields in the North Sea. This excellent report clearly pointed out the problems to be solved in marine geotechnology and what must be done in investigations of the sea bed. In the same year two Japanese researchers, Profs. FUKUOKA & NAKASE (1973), gave a special lecture on problems of soil mechanics of the seafloor at the 8th International Conference on Soil Mechanics and Foundation Engineering held in Moscow. EIDE (1974) summarized achievements made in the North Sea fields after the sudden death of BJERRUM in 1973.

An international journal which is devoted to the theory and practice of geotechnical ocean engineering and the geotechnical aspects of marine geosciences, *Marine Geotechnology* (CRANE and RUSSAK, N.Y.), was published in 1975. This journal has continued to publish the latest information on marine geotechnology and related geosciences. In the U.S.A. a research project to study the Mississippi Delta sediments, "Shallow Experiment to Assess Storm Waves Affecting the Bottom (SEASWAB)" (GARRISON, 1977) was started under

the leadership of the Geological Survey. Six governmental organizations and universities jointly took part in the project and in 1976 a symposium on the results of the project was held, accepting public contributions on the subject. The papers were published in a special issue of *Marine Geotechnology* (RICHARDS, 1977). Although the contributions were mainly concerned with the underconsolidated Mississippi Delta sediments, the volume entitled "Marine Slope Stability Volume" covered a wide spectrum of marine geotechnology. SANGREY (1977), especially, gave an excellent state-of-the-art report. On the other hand, the National Oceanic and Atmospheric Administration in the U.S.A. independently carried out a project, "Marine Geotechnical/Rational Use of the Sea Floor (RUSEF)" (BENNETT, 1978; NASTAV *et al.*, 1980). The areas covered by the project were the Gulf of Mexico and the Atlantic Ocean part of the United States, and several contributions were published from the project (BENNETT *et al.*, 1977, 1979, 1981; HULBERT *et al.*, 1981).

The development of marine geotechnological studies at the North Sea fields after the general review of EIDE (1974) was summarized in *Marine Geotechnology* Vol. 3, (1979) (*e.g.*, ANDRESEN *et al.*, de RUITER & BERINGEN, EIDE *et al.*, SCHJETNE *et al.*).

From 1973 through 1979 the Subcommittee on Ocean Development, the Japanese Society of Soil Mechanics and Foundation Engineering, published a series of books on Offshore Surveys and Structure Foundations. A textbook for geotechnical engineers at work in the North Sea development project was published in Great Britain in 1976 (GEORGE & WOOD, 1976). The chapters of soil mechanics by SCHOFIELD were based on the principles of critical state soil mechanics (SCHOFIELD & WROTH, 1968). In France Le TIRANT (1979) published a text for offshore soil mechanics, which is akin to a guideline book. ALMAGAR (1982a, b) reviewed a wide spectrum of literatures on marine geology, marine geophysics, and marine geotechnology and presented an excellent report for geologists. NAKASE (1984) published a text of offshore soil mechanics in

Japanese.

From 1979 the Offshore Technology Conference has held annually in Houston, U.S.A., under the sponsorship of nine related societies and institutes in the U.S.A., and many papers have been submitted to the conferences. The conferences have also contributed to the exchange of the latest information on ocean developments in the world. Many international conferences and symposia have been held singularly, *e.g.*, NATO Conference on Marine Slides and Other Mass Movements (SAXOV & NIEUWENHUIS, 1980) and IUTAM '83 Symposium on Seabed Mechanics (DENNESS, 1984), or regularly, *e.g.*, Behavior of Offshore Structures (BOSS) every three years. In Japan the first symposium on marine soil mechanics was held under the sponsorship of the Japanese Society of Soil Mechanics and Foundation Engineering in 1982 (Subcommittee on Submarine Soil Mechanics, 1982). An International Conference entitled "Ocean Space '85" sponsored by Nihon University in Tokyo was held in 1985 (KATO, 1985).

Recently offshore oil and gas fields have been explored in such arctic areas as in the Baltic Sea and off Alaska, but cold region marine geotechnology requires to be developed even further (BEA, 1984; WATT, 1984; VACHE & Zaleski-ZAMENHOF, 1985). The International Symposium on Offshore Mechanics and Arctic Engineering (OMAE) has been held every year since 1981 and a session on Offshore Geotechnical Engineering has accepted interesting papers in this field.

Submarine sediments

Submarine sediments consist of soil particles, organic remains and seawater as the pore fluid which often contains dissolved or occluded gases. With increasing water depths submarine sediments suffer from high hydrostatic water pressure. In shallow waters less than about 100 m the seafloor often experiences the repeated loading induced by the passage of rough waves. The temperature of submarine sediments is usually lower than 10° C.

Submarine sediments on continental shelves

and slopes are terrigenous. Fluctuations in sea level and climatic change after the peak of the Würm Age, geomorphology, geology and hydrology of the continents from which the sediments were derived have greatly influenced the distribution of these sediments. For example, the majority of the bottom of the North Sea is covered by dense sand. Scattered over the area, pockets of coarser material (terminal moraines) and gravel are found. Other areas are covered with clay. The distribution of these sediments is explained by the advance and retreat of the glaciers of the Würm Age and the fluctuation of the sea level (BJERRUM, 1973).

The submarine sediments lying along the Japanese Islands were classified into four groups by HOSHINO (1958). They are (1) sediments in estuaries mainly consisting of sandy soil, (2) sediments in straits consisting of gravel soil in the central part and sandy soil on coastal sides, (3) sediments in bays where fine soil deposits in the central part, and (4) outer continental shelf sediments from fine to coarse soils whose distribution is controlled by the oceanographical conditions and seawater chemistry. Since the Japanese Islands are young orogenic belts, high mountain chains run along the arcuate islands in their central parts and narrow low lands develop along large rivers and coastal zones. Almost all the rivers in the Japanese Islands are swift streams, and in the estuaries coarse sediments are transported by the swift streams. The shallowest water depth from which fine sediments distribute is called the "mud-line". The deeper the "mud-line", the rougher the ocean conditions near the estuary are and the smaller the volume of fine sediments transported into the estuary is.

The straits around the Japanese Islands are divided into those three groups by their maximum water depths, which indicate the difference in the geological stages of the formation of each strait. The geological stages were pre-Würm, early Würm (70,000—50,000 BP), and post Würm (after 10,000 BP, Holocene).

There are two types of bays around the Japanese Islands. One was formed by the

subsiding crustal movement from the late Quaternary Period. The water depth at the mouth of this type of bay is in excess of 200 m and the sediments are similar to those of the outer ocean. The other type is formed by the rise in water level after the Würm Age. However, the crustal movement and the sea level change have occurred closely together around the Japanese Islands, and in many bays it is difficult to distinguish between the two effects.

Two terrace planes are found on the outer continental shelves. One is at a water depth of 40—50 m and the other is in the tidal zone. The origin of these terrace planes is sedimentary (submerged delta planes) or erosional (abrasion terraces). The sediments on the submerged terraces are well-sorted gravelly and sandy soils, which are mainly found in the Japan Sea. The sediments on the abrasion terraces are ill-sorted coarse gravelly soils, which are mainly found on the Pacific Ocean side.

The surface geology of the seafloor adjacent to the Japanese Islands has been studied from a geological standpoint (HOSHINO, 1958) or at each harbor construction site or coastal reservation site geotechnical investigations have been carried out (Subcommittee on Ocean Development, 1979). However, general reviews from a geotechnical point of view as carried out by KELLER (1967), NOORANY & GIZIENSKI (1970) and KELLER & BENNETT (1970) are absent for the submarine sediments around the Japanese Islands except for the sediments in the Seto Inland Sea (OKUSA *et al.*, 1983).

Strength and sediment structures of submarine sediments

It is well-known in soil mechanics that at any point of a surface in a submarine sediment the shearing resistance, s , is roughly represented by

$$s = c' + (\gamma'z - u_w) \tan \phi' \quad (1)$$

where c' is the cohesion, ϕ' is the true angle of shearing resistance, γ' is the submerged unit weight of the sediment, z is the depth below the seafloor and u_w is the pore pressure in

Fig. 1. Grain size of sediment and deposit structure.

- I : Adhesion structure (clay—fine silt)
- II : Metastable structure (coarse silt—fine sand)
- III : Stable structure (medium sand—gravel)

M_r : Resisting couple

M : Overturning couple

W : Particle weight

d : Arm length of two contacting particles

excess of the hydrostatic pressure at the point under consideration. The cohesion, c' , represents the shearing resistance of the sediment on the seafloor and is mobilized by the molecular attractive force between the soil particles and is called “zero friction” (TERZAGHI, 1925). For coarse sediments $c'=0$, and for fine sediments, for example, on the lake floor of Sweden c' was reported to be in a range of 5.9—7.8 kPa (JAKOBSON, 1953). Eq. (1) is rewritten in the form,

$$s=c'+U\gamma'z \tan\phi', \quad U=1-u_w/\gamma'z \quad (2)$$

where U is the degree of consolidation. When $U=1$, the sediment is in a normally consolidated state, and the sediment with $U<1$ is underconsolidated. In sandy and gravelly sediments u_w is always equal to or close

to zero, and U becomes unity directly after sedimentation. With decreasing grain size the initial void ratio of a sediment, e_0 , i.e. the ratio between the volume of voids and that of solid particles in the sediment, increases. If e_0 is large enough and the “zero friction” c' is not large, the effect of vibrations, for example, produced by an earthquake or explosion or other disturbances, on the structure of the sediment increases (TERZAGHI, 1955, 1957). This is well-explained by the mechanism of a particle sinking in the water onto the surface of the sediment (Fig. 1). As soon as a sinking particle with a diameter D settles on the surface of the sediment, it tends to roll or slide into the most stable position. This tendency is resisted by the molecular attraction, c' , which acts at the point of initial contact between the particle and the sediment surface. If the rolling or sliding moment, $M=W \times d$ is greater than the resisting moment, M_r , which is proportional to the “zero friction”, the particle will settle at a stable position. The particle weight, W , is proportional to the third power of D and the arm length, d , is proportional to D . Therefore, the overturning couple, M , is proportional to the fourth power of D . If the “zero friction” is assumed to be proportional to the specific surface of the particle, the resisting moment is inversely proportional to D . Therefore, in a range of diameters a little smaller than that corresponding to the intersection of the two curves of M and M_r in Fig. 1 the probability that the particles will assume stable positions decreases and the sediment takes the metastable structure (TERZAGHI, 1957). The grain size distribution of a sediment with the metastable structure falls in the range characteristic for coarse silts to fine sands which are susceptible to liquefaction.

A metastable sediment easily collapses on slight excitement associated with a considerable decrease in the void ratio. If the sediment is saturated, the weight of the solid particles is temporarily transferred from the points of contact with their neighbors onto the pore water. Consequently, the hydrostatic pressure at any depth z increases from

Fig. 2. Slump feature off Kanbara, Shizuoka, Suruga Bay. A and B : Sampling points.

Fig. 3. Slump feature off Itoigawa, Japan Sea.

Fig. 4. Submarine canyon off Kujukurihama, Pacific Ocean (solid line: survey in 1963; broken line: before 1963).

Fig. 5. Grain size distributions of samples from A (open circle) and B (solid circle). The samples are mixture of 5—15 cm gravels, sands and mud, which suggests the slump origin.

its normal value $\gamma_w z$ by an amount, which is close to the submerged sediment weight $\gamma' z$ located between the seafloor and depth z , resulting in an expulsion of the water with the particles. Here γ_w is the unit weight of water. This phenomenon is liquefaction. The liquefied sediment flows on the submarine slope as the average degree of consolida-

tion increases and finally comes to rest forming a fan-like sedimentary plain when U becomes equal to unity. The time and distance to which the liquefied sediment can travel during the transition from the liquefied to the solid state depends on the permeability of the sediment. The time increases with decreasing permeability, as a consequence, with decreas-

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Fig. 7. Schematic diagrams of types of marine instabilities found in the Mississippi Delta (After GARRISON, 1977).

sively studied in the Mississippi Delta region, where more than 500 offshore structures have been constructed and hundreds of kilometers of pipelines have been installed (BEA, 1971; BEA & AUDIBERT, 1980; BEA *et al.*, 1983). In this region the submarine topography has been greatly changed by every large hurricane and some portions of the delta front have become creased. "It is not a question of whether or not the sediments move: only when and how much" (BEA & AUDIBERT, 1980). Fig. 6 shows an accident of a platform and change in the seafloor due to a hurricane in the Mississippi Delta (BEA & AUDIBERT, 1980). COLEMAN & GARRISON (1977) clarified the types of submarine instabilities found in the Mississippi Delta as shown in Fig. 7.

TERZAGHI (1957) pointed out that on ac-

count of the fact that the ratio $s/\gamma'z$ is a minimum at a considerable depth in the Mississippi Delta underconsolidated sediments below the seafloor due to the high pore pressure undissipated and the "origin cohesion", the slope failures could be explained in terms of gravity forces and the very low shear strength. However, HENKEL (1970, 1982) demonstrated that in terms of total stresses the slope of the Mississippi Delta (about $\beta=0.5^\circ=0.009$ rad) was not steep enough to initiate the gravity slides even with the very low shear strength ($s/\gamma'z=0.03-0.05$). In terms of effective stresses the resisting force $U \tan \phi' = 0.01-0.17$ is greater than the sliding force $\tan \beta$ and it was impossible to explain the initiation of gravity slides. He was the first to introduce the role of waves in the stability analysis of submarine sediments. He assumed the sediment to be rigid and a sinusoidal transient pressure change with the wavelength, L , and pressure amplitude, Δp , on the seafloor to be the essentially undrained loading. The sliding couple, M_1 , by the self weight along the circular slip surface in Fig. 8 is given by

$$M_1 = 2x^3 \beta \gamma' / 3 \quad (3)$$

and the disturbing moment by the wave pressure, M_2 , is given by

$$M_2 = 2\Delta p (\sin ax - ax \cos ax) / a^2 \quad (4)$$

where $a = 2\pi/L$ is the wave number.

The moment of resistance, M_3 , that can be mobilized within the soil is given by

$$M_3 = 2x^3 \gamma' (s/\gamma'z) \frac{(\sin \theta - \theta \cos \theta)}{\sin^3 \theta} \quad (5)$$

The sediment will be at the point of failure when $M_1 + M_2 = M_3$ and when $M_1 + M_2 > M_3$ movement will take place. HENKEL introduced appropriate values of $s/\gamma'z = 0.04$, $\beta = 0.008$, $\gamma' = 6.86 \text{ kN/m}^3$ in the Mississippi Delta and proved that the minimum value of $\Delta p = 2.4 \text{ kPa}$ with a wavelength of $L = 61 \text{ m}$ can cause failures for very shallow circles and that $\Delta p = 24 \text{ kPa}$ with a wavelength of $L = 183 \text{ m}$ can cause failures to depths of about 50 m. His paper was monumental in that it first took the wave force into account for the submarine instability problem. BJERRUM (1973) explained the high density of the fine sand in the North Sea by the cyclic wave force proposed

Fig. 8. Influence of wave pressure on submarine rotational sliding (after HENKEL, 1970).

θ : Central angle of slip arc
 β : Slope of seafloor
 d : Maximum penetration depth of slip circle
 $2x$: Length of failure
 L : Wavelength

Fig. 9. Orkdals Fjord flow slides and breakage of cables (after ANDRESEN & BJERRUM, 1967).

by HENKEL.

There are many papers on the unique topography and geotechnical properties of the Mississippi Delta sediments (SHEPARD, 1955; SHEPARD *et al.*, 1978; PRIOR & COLEMAN, 1978; BOOTH & GARRISON, 1978). The unique sedimentary environments of the Mississippi Delta have produced very specific features of fine sediment structures and geotechnical properties which have been studied under the leadership of BENNETT (BENNETT *et al.*, 1977, 1979, 1981).

Liquefiable Submarine Sediments. Liquefiable sediments have been deposited from the sandy coast offshore, in fjords, at submarine areas where in the ice age the seawater retreated, and at various other locations. These sediments collapse in the form of catastrophic flow slides.

On the shores of the straits between the islands forming part of the Province of Zeeland no less than 229 major flow slides have occurred, involving the displacement of 25,000,000 m³ of sediments between 1881 and 1946

(TERZAGHI, 1957). The original slope angle of about $\beta=15^\circ$ decreased after the slide to about 5° . The flow slides along the coast of Zeeland commonly occur at extreme low tide after exceptionally high spring tides. This suggests that the collapse of the metastable structure of the sediment is caused by the seepage pressure of the groundwater which returns to the ocean during receding tide. The flow speed is inferred to be of the order of a magnitude of 15 km/h.

Fig. 9 shows the fine sand flow slide in the inner portion of the Orkdals Fjord on May 2, 1930, and the subsequent submarine cable breaks (ANDRESEN & BJERRUM, 1967). The bottom of the fjord is covered with silty sand, resting on bedrock. The slide started at point A close to the southwestern end of the fjord where a small fill had recently been deposited along the shoreline. At the time of an exceptionally low tide the fill, about 500 m wide and 1,500 m in volume moved out into the sea along the shoreline. A few minutes after the slide at point A a new slide occurred at site B whose upper edge scar had a length of 600–700 m. Finally, about 7 minutes after slide A, a third slide took place at point C. At the same time the submarine cable C_1 located at a distance of about 3 km from point A snapped, and 1h52 m after slide A cable C_2 at a distance of about 20 km from A went out of service. There was no evidence of sliding between site A and cable C_2 . The velocity at which the breakdown of the equilibrium of the sediment advanced from A to cable C_1 was about 26 km/h on a submarine slope of 5/100–10/100, and from C_1 to C_2 about 10 km/h over a distance of 17 km on an average slope of practically zero. The first slide is considered to have been caused by the seepage flow of the onland groundwater through the fissures in the bedrock at the time of the exceptionally low tide (ANDRESEN & BJERRUM, 1967). The failed volume totalled 10,000,000 m³ by the three first slides.

Large scale submarine cable breakage occurred on the Grand Banks south of the shore of Newfoundland immediately after the Grand Banks earthquake on November 18, 1929, (M

=7.2) (TERZAGHI, 1957; SHEPARD, 1973). From this earthquake 13 submarine cables installed on the continental slope and the oceanic basin of about 5,000 m water were broken one after the other from the shallow water to the deep. It took about 13 hours between the first breakage which occurred immediately after the shock and the final breakage. These breakages occurred over a distance of about 270 km on the continental slope of a gradient of 1.9/100, 100 km/h at the foot of the slope, and 60 km/h on the continental rise of a gradient of 0.53/100, 20 km/h at the end of the path where the seafloor gradient was 0.04/100. TERZAGHI (1957) inclined to believe that the extraordinary speed of propagation of the disturbance represents the velocity of the advance of the boundary of the liquefied portion of the sediments underlying the seafloor and not the velocity at which the slide material moved over the floor. He also considered the same mechanism to account for the breakage of cable C_2 in the Orkdals Fjord failure. However, TERZAGHI's idea has not satisfactorily been explained yet on the basis of soil mechanics.

Instabilities of Other Sediments. From the viewpoint of engineering geology, the response of usually stable sediments to such dynamic loads as earthquakes and ocean waves is of importance in offshore structure installations.

The dynamic response of sediments during earthquakes has been extensively investigated by Japanese researchers since the 1964 Niigata earthquake (YOSHIMI, 1980; TASTUOKA & ADACHI, 1982; SHIBATA, 1985; ISHIHARA, 1985) and their contributions were used in the development of the North Sea fields (EIDE, 1974).

Repeated wave loads act first in one direction and then in the opposite direction to structures and sediments. Therefore, a stress reversal occurs during the passage of a wave, and the structures are subjected to hours of cyclic loading. The sediment beneath a structure experiences a series of shear stress applications alternating between a positive and a negative value of about the same magnitude. For example, under the North Sea conditions the duration of storm waves of about a 15-

second period will be about 3—9 hours, and the degradation will continue for another 6—9 hours. These conditions are similar to those in the Japan Sea in the winter, though the wave period in the Japan Sea is smaller than that of the North Sea. The stress conditions induced by these storm waves are comparable to what occurs during an earthquake characterized by acceleration as high as 0.2—0.4 g (BJERRUM, 1973). The duration of shocks of an earthquake is about one minute at its maximum with a dominant period of around 0.1 seconds. Therefore, the cycle number is about 600, while the cycle number for storm waves in the North Sea is 720—2,700. A gravity type structure in the Ekofisk field suffered from high storm waves whose maximum height (21—22 m) corresponded to about 90 % of the design wave of 24 m. The storm caused 5 cm of settlement within the fine, dense sand layer of about 25 m in the period of the duration (5 days) (EIDE, 1974).

The effect of repeated wave loads has been studied on submarine sediments of dense sands and clayey soils under drained and undrained conditions (EIDE, 1974; LEE & FOCHT, 1975; GARRISON, 1977; Proceedings of Int. Conf. Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 1981; ALMAGAR, 1982 a, b).

Deep sea sediments taken by the Mohole project and the DSD project have been studied from a geotechnical point of view (HAMILTON, 1964; Inderbitzen, 1974). Specific characteristics have been found for the deep sea sediments such as a nearly constant void ratio with depths in spite of increasing strengths (MOORE, 1964; NAKASE & KAMEI, 1984). These characteristics may be related to a late accumulation and the seawater chemistry in the pores (SANGREY, 1977), but geotechnical characteristics of deep sea sediments have not been disclosed yet.

Recently calcareous sediments have received attention from an engineering point of view (NAMBIAR *et al.*, 1985; POULOS, 1985).

Turbidity currents may occur in any type of sediment. The problems on the turbidity current were fully reviewed from a geological

point by HOSHINO (1965) and from a mechanical viewpoint by MORGENSTERN (1967).

Submarine soil flows including liquefaction flows and clay slides were reviewed by EDGERS & KARLSRUD (1982).

On October 19, 1979, a catastrophic flow slide occurred on the upper continental shelf off Nice (Group ESCYANICE, 1980). At around 2 p.m., following a lowering of the sea level, a tsunami at an amplitude of several meters reached the coastline south of Antibes. Several oscillations lasted for 4 hours with decreasing amplitude, which attacked a shoreline of about 100 km in length. About the same time, an embankment area along the coast 300 m wide and long collapsed within a few seconds. After the event the seafloor in that area was found at a depth of 50 m. At 5 : 45 p.m. and 10 : 00 p.m. two submarine cables located on the seafloor of about 2,500 m depth at distances of 80 km and 110 km off Nice snapped. The velocity of propagation of the disturbance was about 13 km/h on the nearly flat seafloor. The collapse might have been a kind of flow slide.

On March 22 and 23, 1974, during the passage of a winter depression (990 mb) in the Japan Sea, the coast of Awashima Island about 20 km off the western coast of northeast Japan collapsed from the attack of rough waves which were of the order of magnitude of 4 m wave height, 110 m wavelength and 8.5 s period with winds of 20 m/s. The rough weather continued from the morning of March 22 to midnight for about 18 hours. The southeastern coast of the island running NE—SW had been suffering from waves induced by the winds from south or south-southwest. At about 3 p.m. small scale fixed fishery nets at a water depth of about 30 m were moved by waves or currents in the northeastern direction at a distance of about 4.5 km along the coast. At about 5 p.m. the No. 3 breakwater about 150 m long extruding perpendicular to the coast line into the sea to a water depth of 15 m at the southwestern end of the village began to tilt toward the sea. The winds were at their maximum between 8 p.m. —10 p.m. At 11 : 30 p.m. the village

Fig. 10. Contour lines before and after the Awashima failure.

office began to tilt and at 00 a.m. on the 23rd the coastal side of the kindergarden sank. At 0 : 10 a.m. the kindergarden gave away into the sea and at 1 : 00 a.m. the second breakwater was washed away. The village office completely toppled into the sea at about 1 : 10 a.m.. The degradation of the rough weather began around 3 a.m. and by this time the top half of the No. 3 breakwater and the top 10 m of the No. 1 breakwater collapsed (Fig. 10) (TOYOSHIMA, 1986). As a result 500 m of the coast failed. The sea bottom was covered with the Holocene silt and fine sand intercalated with gravelly sand. About 1,000,000 m³ of soil was displaced. The failure would have been initiated by the shock of the rough waves and the seepage pressure of the groundwater at those times when the trough of waves was on the foreshore. However, the epicenter of the 1964 Niigata earthquake ($M=7.5$) located in the sea several kilometers south of Awashima Island which was the very center of the aftershock region and the area of tsunami origination. The island was uplifted by about 1.5 m due to the earthquake. The sediments around Awashima Is-

land must have been disturbed and weakened by the earthquake shock. Therefore, the slide might have been an aftereffect of the shock or a kind of delayed failure due to the earthquake triggered by the rough waves.

Pore pressures in submarine sediments and submarine instabilities

In order to analyze the instability of submarine sediments induced by rough waves and earthquakes and to understand the consolidation condition, it is one of the most important tasks in submarine engineering geology to disclose the pore pressures in submarine sediments. It was in the 1970's that measurements of submarine sediment pore pressures were begun. Many papers have been published since 1975 in relation to instabilities of sediments and offshore structures and degree of consolidation of submarine sediments (RICHARDS *et al.*, 1975; BENNETT *et al.*, 1976; HIRST & RICHARDS, 1977; BENNETT, 1977; SUHAYDA 1977; DUNLAP *et al.*, 1978; BENNETT & FARIS, 1979; OKUSA & UCHIDA, 1980; EIDE *et al.*, 1982; HULBERT & BENNETT, 1982; OKUSA *et al.*, 1984; MAENO & HASEGAWA, 1985; OKUSA,

1985a; ZEN & UMEHARA, 1985). Findings of these measurements showed that (1) wave-induced pressures are transferred not hydrostatically to the sediment pore fluid being diminished, (2) accumulation of pore pressures occurs during the passage of storm waves, (3) gases contained in submarine sediments have an effect on the fluctuation of pore pressures, (4) the fluctuation of pore pressures may be out of phase with that of ocean wave pressures on the seafloor, and (5) wave-induced pore pressures may cause instabilities of submarine sediments.

The problems of wave-induced pore pressure in submarine sediments have received much detailed attention to date in relation to wave damping (REID & KAJIURA, 1957) and hydraulics (SLEATH, 1970; MOSHAGEN & TØRUM 1975; PREVOST *et al.*, 1975) under various assumptions of the wave and the seabed. From a geotechnical viewpoint the theories presented by MADSEN (1978), YAMAMOTO *et al.* (1978) and YAMAMOTO (1981) are the most general ones which are based on the assumptions of perfectly elastic sediments and the validity of Darcy's law for alternating flow through the sediment pores. The solutions by them are essentially the same and are represented in terms of the displacement components and pore pressure. However, their solutions indicate that the displacements, as a consequence, effective stresses, and pore pressure depend only on the wavelength and wave height on the seafloor and do not depend on the sediment characteristics (*e.g.* the permeability and deformability).

OKUSA (1985b) has solved the problems of the wave-induced pore pressure and stresses in a poro-elastic sediment, using the compatibility conditions under elastic equilibrium. The solutions are the same as those by MADSEN (1978) and YAMAMOTO *et al.* (1978), but are represented in terms of the effective stresses and pore pressure, because the fundamental equations are reduced to the fourth order linear differential equations instead of the sixth order ones. In order to explain the difference of the sediment response due to soil types OKUSA (1985b) considered the effect of

Fig. 11. Wave-induced disturbed zone in submarine sediments.

Wave period : $T=20$ s

Wavelength : $L=521.17$ m

Wave height : $H=30$ m

Water depth : $d=100$ m

Pore pressure coefficient $B : 0.9$

a small amount of the occluded gas which may not be uncommon in submarine sediment pores (ESRIG & KIRBY, 1977). When a submarine sediment contains a small amount of occluded gas, the pore pressure and effective stresses induced by wave action are represented in two parts. One depends only on the wavelength and wave height and the other on both the sediment and wave characteristics. The wave-induced negative effective normal stresses become greater under the trough of wave for the gas-laden sediment. A zone whose in-situ vertical effective normal stress or the in-situ mean effective normal stress is turned into zero is formed in a gas-laden sediment under certain wave and sediment conditions (Fig. 11). SKEMPTON's pore pressure coefficient B (SKEMPTON, 1954),

$$B = 1 / (1 + n\beta/\alpha) \quad (6)$$

plays a role in controlling the wave-induced instability of a submarine sediment. Where n

Fig. 12. Relationship between the degree of saturation (S) of soils at various depths from the sea surface and SKEMTON's pore pressure coefficient B .

is the porosity of the sediment, β is the compressibility of the pore fluid, and α is the compressibility of the porous skeleton. Coefficient B can be derived from the fact that under undrained condition the volume change in a soil structure under loading is equal to the change in the void which is filled with the pore fluid. B value rapidly decreases from 1.0, even when the degree of saturation, *i.e.* the ratio between the water volume and the total volume of voids in a sediment, decreases slightly (Fig. 12).

The theory by MADSEN and YAMAMOTO *et al.* has been applied to the analysis of wave-induced stresses in the sediments around a pipe (MEI & FODA, 1981) and a caisson (MYNETT & MEI, 1982). The same theory has been applied to the consideration of cyclic rotation of principal stress directions as induced by wave loads and related experiments have been conducted in relation to wave-induced liquefaction (ISHIHARA & TOWHATA 1983; ISHIHARA & YAMAZAKI, 1984).

Other developments in the problems of wave-induced stresses and pore pressure are found in many papers (FINN *et al.*, 1983; DEMARS, 1983; NATARAYA & GILL, 1983; TSUI & HELFRICH, 1983; KRAFT & HELFRICH, 1983; KRAFT *et al.*, 1985). YAMAMOTO (1983) has developed a non-linear theory of wave-induced stresses and pore pressure taking Coulomb internal damping into account. SEED &

RAHMAN (1978) considered the effect of cyclic wave loadings on liquefaction of cohesionless elastic soil on the basis of the established relationship between the liquefaction strength and cycle number of repeated loadings.

Gases in submarine sediments

Gases in submarine sediments have an important bearing upon (1) the stress change in a submarine sediment sample while being lifted up to atmospheric pressure, (2) characteristics of sound propagation during seismic and sonic prospecting, (3) wave-induced stresses and pore pressures as already stated in the preceding chapter, (4) erosion features of submarine sediments, and (5) occurrence of underconsolidation (BENNETT, 1977; HIRST & RICHARDS, 1977; HULBERT & BENNETT, 1982). In this chapter the problems associated with (1) and (4) are briefly discussed.

Effects of Unsaturation on Submarine Sediments.

It is assumed that the water and gas phases within the sediments constitute a single compressible fluid and that the gas-laden sediments obey the normal definition of effective stress principle in soil mechanics. The effect of gas diffusing through pore water and the movement of water vapor are also ignored. These conditions are likely to occur if the degree of saturation is sufficiently as high as 85% or more so that the gas bubbles are occluded and smaller than the normal void spaces.

When a sediment sample with the in-situ degree of saturation S and pore pressure u is taken up to the sea surface, its pore pressure and degree of saturation change to u_0 and S_0 , respectively. From HENRY's law and BOYLE's law under a constant temperature (ESRIG & KIRBY, 1977),

$$u(1/S - 1 + H) = u_0(1/S_0 - 1 + H) \quad (7)$$

where H is HENRY's solubility constant and the pressures are taken to be absolute. If u_0 and u are the same as the atmospheric pressure and in-situ hydrostatic pressure, the in-situ degree of saturation S can be evaluated by measuring the shipboard degree of saturation S_0 . The degree of saturation, S , can be uniquely evaluated by measuring the ship-

Fig. 13. Calculated variations of SKEMPTON's pore pressure coefficient B for three gas-laden sediments and the degree of saturation S with depth from the sea surface where the degree of saturation $S_0=80\%$. 1, 2 and 3: Variations of SKEMPTON's pore pressure coefficient B , 4: Variation of the degree of saturation

board degree of saturation, S_0 , irrespective of characteristics of sediments. The curve 4 in Fig. 13 shows the variation in the degree of saturation with depth for any sediment with $S_0=80\%$. It is clear from Eq. (7) and the curve 4 in Fig. 13 that when a gas-laden sediment or sediment with gas dissolved water is taken up to the sea surface, the degree of saturation decreases, and the quality of the sample becomes poor (FLORIN, 1961; OKUMURA, 1974).

When a load increment Δp is applied on a

gas-laden sediment, this is divided into the effective stress $\Delta \bar{p}$ and the pore pressure Δu which are related with SKEMPTON's pore pressure coefficient B , Eq. (6),

$$\Delta u / \Delta p = B = 1 / (1 + n\beta / \alpha) \quad (8)$$

The compressibility of the pore fluid composed of water and gas, β , is approximately expressed by

$$\beta = S\beta_w + (1-S)\beta_a \quad (9)$$

where β_w is the compressibility of the water, and β_a is the compressibility of the gas. Eq. (9) is based on the assumption that the effect of surface tension and the movement of gas within the solution are ignored. The compressibility of a gas during isothermal processes, β_a , is represented by $1/u$. Then Eq. (8) becomes,

$$B = 1 / \left\{ 1 + \frac{n[S\beta_w + (1-S)/u]}{\alpha} \right\} \quad (10)$$

This means that the variation in SKEMPTON's pore pressure coefficient B depends on the compressibility of a sediment skeleton, α , the degree of saturation and porosity of a sediment. The curves 1, 2 and 3 in Fig. 13 show the variations in B with depth for three sediments whose shipboard degree of saturation is equally $S_0=80\%$. It is clear from the curves that SKEMPTON's pore pressure coefficient B is very sensitive to the compressibility of sediment skeleton, and the smaller the compressibility, the greater the variation in B for a small change in the degree of saturation. However, the compressibility of a submarine sediment skeleton, α , generally decreases with increasing depths, and for soft sediments near the seafloor, α is very large (very compressible) compared to $[S\beta_w + (1-S)/u]$. Then other curves in which $B=1$ on the seafloor can be obtained (ESRIG & KIRBY, 1977).

In any case, the effect of SKEMPTON's pore pressure coefficient, B , smaller than unity is great when external loads are applied on the seafloor. Measurements of SKEMPTON's pore pressure coefficient, B , in submarine sediments are essential for the evaluation of sediment instability.

Pockmarks. Shallow crater-like or elongated depressions on the seafloor are called pockmarks, which have been discovered in such

Fig. 14. Pockmarks.

parts of the world as in Nova Scotia, the Gulf of Mexico, the South China Sea, the North Sea etc during the past decade. In the South Fladen area, the North Sea, about 1,900 pockmarks were found in an area of 57 km² and the area of the pockmarks covered 3.75% of the overall area, with an eroded volume of about 2,400,000 m³ (JUDD, 1981). The pockmarks vary in size from 5 m to about 150 m and in depth from 1 m to 15 m (Fig. 14). Crater-like depressions are generally found in regions where the sediment consists of soft, silty soils, while elongated depressions occur in areas where the surface sedimentary layers consist of fine sands (HOVLAND, 1982, 1983, 1984; HOVLAND & GUNDMESTAD, 1984). The latter is sometimes called "mottled seabed". In some areas "fossil (buried) pockmarks" can be seen on seismic records on the unconformity plane beneath the surface sedimentary layers. In the North Sea the pockmarks are found at water depths of 150 m through 300 m.

The walls of pockmarks may bear evidence of slumping, and coarse material (gravels) has been found in their center. Small faults in the upper sedimentary units may also be seen.

Similar features were found on a southeastern coast of Izu Peninsula, Japan, where

crater-like depressions of several meters in diameter and about 0.5 m in depth have been often formed at waters of 1–6 m after storm waves (OKUSA *et al.*, 1985). The coast is a beach, and deaths from drowning were caused by the depressions.

Most pockmarks are probably gas-induced features and found only in soft, fine-grained, marine and glaciomarine sediments. They are probably caused by shallow or deep seated gas (or light fluid) released through the seabed, whereby the finest particles are thrown into suspension and redistributed by near-bottom current (HOVLAND, 1984). Pockmarks found in shallow waters in Japan are in fine sand whose grain size distributions fall exactly in the middle of the range characteristic for sands which are susceptible to liquefaction during earthquakes. Near the coast where pockmarks were found are located several hot spring sites, and on the river floors near the coast hot springs can be found gushing out. Although the coast is located at about 35°N, this is the only one mangroove marsh at the river mouth near the coast of the Honshu Island of Japan. Therefore, the combination of the migration of the hot spring with gas and rough waves may be responsible for liquefaction of the sediment on this coast.

Platforms and pipelines in the pockmarked areas should be assumed that pockmarks do not pose a significant threat to their instabilities. Active pockmark areas where pockmarks are being formed at present are especially dangerous for the installations of offshore structures. HOVLAND & GUNDRESTAD (1984) proposed some countermeasures to "freshly" formed or "active" pockmarks for gravity structures, piled structures and pipelines. However, direct visual observation or indirect proof of "freshly" formed or "active" pockmarks is still lacking. If the origin of pockmarks is really associated with gas release, SKEMPTON's pore pressure coefficient, B , of the sediment would be decreased as pointed out in the preceding chapter at the time of the formation of pockmarks, and the response of the sediment to external loads would be very different from an ordinary state.

Concluding remarks

Importance of geology for the development of geotechnology and engineering geology has been stressed by many outstanding researchers (e.g. TERZAGHI, 1929, 1955; PECK, 1973, 1977). "Geology should be used to greater advantage" (PECK, 1973). "TERZAGHI considered soil mechanics to be a quantified aspect of applied or engineering geology" (PECK, 1977). The same holds true for marine geotechnology and marine engineering geology. Many excellent contributions on marine geotechnology have been published in geological and geomorphological journals, reports and bulletins in foreign countries. Some of them are cited in this paper. Also quite a few geologists have taken part in the study of marine geotechnology and have played important roles in the development of this interdisciplinary collaboration of science and technology in foreign countries. In contrast to this few literatures on marine geotechnology have appeared in Japanese geological journals and so on, although most of the graduates from geology departments have been engaged in the field of engineering geology and oil exploitation including marine work.

The author strongly wishes that this review

serves as a good initiative for geologists to take part in the study of marine geotechnology. "Engineering geology has its roots in the field and can be learnt by painstaking field observation of how a site works" (HENKEL, 1982).

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** : in Japanese with English abstract.

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(要 旨)

OKUSA, S., 1986 : Marine geotechnology—A new interdisciplinary branch of science and technology. *Jour. Geol. Soc. Japan*, 92, 879-903. (大草重康, 1986 : 海底の土木地質学—新しい学際的科学技術. 地質雑, 92, 879-903.)

海底地盤の土木地質学の発展過程, 研究の現状, および問題点を総括した. この新しい学際的分野の研究対象, 目的, 課題を明らかにしたうえで, この分野の歴史をスケッチした.

海底地盤の土木地質学的諸問題のうち, 本論でとりあげたものは, (1)海底地盤の堆積学的, 物理的, 力学的特性, (2)海底地すべり等に関連する海底地盤の不安定性, (3)海底地盤の不安定に関連する波浪による地盤内間隙水圧変動, (4)海底堆積物に含まれるガスと地盤の応力条件およびボックマークの形成, である.

海底堆積物の地形地質的形成条件および現在の地形地質過程の解明が, 海底の土木地質学を進歩させるうえできわめて重要である.