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Earth reinforcement – West and east

Masami Fukuoka
Science University of Tokyo, Noda, Japan

ABSTRACT: Natural reinforcing materials have been used in both west and east since long ago. Modern reinforcing materials are steel and geosynthetics. Much modern technology for reinforcing earth were mainly invented and developed in the west, but development of the technology has been carried out in the east as well. The past and present circumstances in the east are introduced in connection with the west.

1 INTRODUCTION

The reason for holding the International Symposium on Soil Reinforcement in Kyushu may be attributed to the fact that the level of engineering in this area has been high in both research and practical works. It is very well known that Professor Toyotoshi Yamanouchi, Chairman of the Steering Committee, Professor Emeritus of Kyushu University and Professor of Kyushu Sangyo University, has been a powerful leader for many years. An investigation committee for soil reinforcement has been established in the Kyushu Branch of the Japanese Society of Soil Mechanics and Foundation Engineering under the chairmanship of Professor M. Ishido, Kyushu Sangyo University, and the report, "Case Records on Soil Improvement, June, 1987", was published as the results of their activities. The report contains 3 chapters. Chapter 1: Reinforcing of soft ground and embankments. Chapter 2: Reinforcing of natural ground. Chapter 3: Literature. The number of items of literature collected is 881, 372 of these are from Japan and 509 from other countries, all of which are written in English. One can see that number of papers published in Japan is not so small, but it is questionable what percentage of papers has been translated and introduced to other countries.

Materials used for reinforcing earth have mainly been steel and petroleum products. As for the petroleum products, the development of new avenues of use has been remarkable, and international technology exchange has become active after the establishment of the international society. The International Geotextile Society was established in 1983, and the Japanese group of geotextiles began to work as early as in 1982 just after the 2nd International Conference in Las Vegas and has been active since then. The number of papers published has reached a considerable figure, but most of the papers have not been translated into English, like those of other countries in the world. Even valuable and interesting papers have not been translated into English. Dr. J. P. Giroud, President of the IGS, attended the Japanese Symposium in December of 1986 and showed a special interest in the presentations, and suggested to publish them for the journal, Geotextiles and Geomembranes. We Japanese must try to publish our papers in English as often as possible. The author assumes that it will not be any use to introduce how imported technology for earth reinforcement has been developed in Japan.

2 NATURAL REINFORCING MATERIALS

Throughout the world, natural reinforcing materials were used from old time. Babylonian constructed ziggurats made of soil mixed with plant stems more than 3,000 years ago. More than 2,000 years ago the Chinese constructed tide embankments by the use of fascine. Romans used mats made of ditch reed. The gabion was introduced to Japan in 6th century. Dutch used the fascine widely to treat soft ground around the 14th century. Shingen Takeda used various kinds of "ushiwaku" (ox frame), "ryogyu", "dai-seigyu" and syakumokugyu", which were combinations of bamboo gabions and logs for river improvement. Earth reiforced

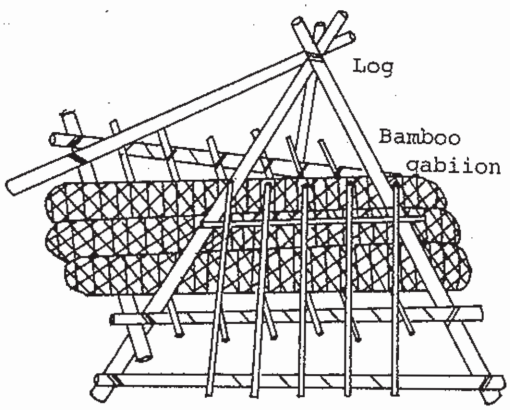


Fig. 1 "Ryogyu" for river work by Shingen Takeda (after K. Aki)

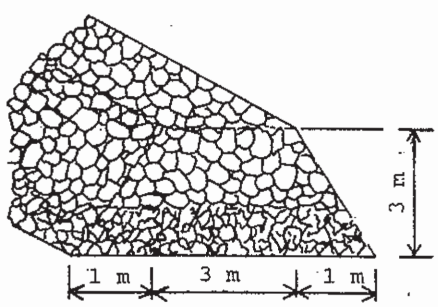


Fig. 2 Embankment reinforced by logs and bambooes for river work by Shingen Takeda (after K. Aki)

with timber, straw and reeds, etc., were used from old time in the east and west. Wooden piles were used to prevent a landslide mass in Japan 200 years ago. Originally, straw bags were used to keep rice in them 2,000 years ago, but straw bags filled with earth were used for forming embankments with steep slopes in Japan. The "sumo" wrestling ring began to be constructed using such sand bags since about 400 years ago.

3 STEEL

Steel wires began to be used to substitute bamboo nets for gabions about 100 years ago in Japan.

3.1 Steel nets

An artificial island was constructed for the purpose of constructing a vertical shaft to transport coal in the Ariake Bay in Kyushu from 1949 to 51. Steel nets were placed on the sea bed to reinforce the soft foundation and to separate the soft clay and the stone mound. Dr. Sadaichi Morita was in charge of this construction work. The thickness of the soft subsoil was about 14 m. Unit weight 14.8 kN/m^3, specific gravity 2.45, void ratio 2.27, angle of internal friction 9°, and cohesion 5 kN/m^2. Height of the fill was about 9 m and its unit weight 20 kN/m^3. The total settlement was estimated to be 2.7 m. The artificial island was round in shape. Its diameter was 178 m at the foot of slope and 120 m at the top of the island. The island was made of reclaimed sand in the middle and surrounded by rocks. The inclination of the slope was 1 : 2.9 on the average, gentle at the lower part and steep at the upper part. A general cross section is shown in Fig. 3. Steel nets named Kawasaki steel nets, Type No. 6 (diameter 4.2 mm) with 18 cm mesh, were placed on the sea bed and filled with rocks of 30 - 50 kg in weight. Morita pointed out the reasons why the nets were used.

(a) The nets embedded in mud under the sea bottom will not rust as they are not exposed to fresh air.

(b) Unequal settlement can be prevented by the placement of nets.

(c) Gently sloped revetments are easy to repair after natural disaster.

(d) Construction cost is the lowest.

The sea bed runs dry about 3 hours for large low tide. The nets were laid by man power, and rocks were transported by boats at high tide, and placed in the right position during low tide. The total area of the nets was 13,000 m^2 and man power needed was 1,957 person days. This construction work was completed without any trouble and the island is still in good condition even after about 40 years. Steel nets have been used occasionally since then.

There was an example of retaining wall on a soft ground with steel nets of ordinary steel bars in the backfill.

Steel nets were used successfully for the construction of a retaining wall for temporary use in the USA. Steel nets are easier to have the stresses on the nets measured than are geotextile nets, as they deform elastically. The author of this steel wire net retaining wall measured

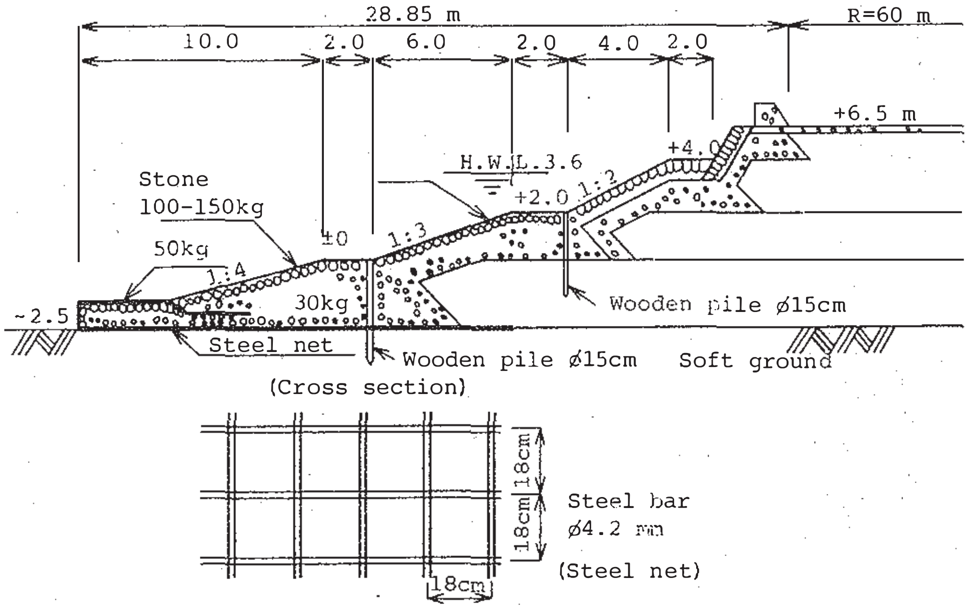


Fig. 3 Steel net reinforcement placed on soft ground, Miike artificial island for colliery, constructed in 1949-1951 (after S. Morita)

strains and stresses of the members and calculated the earth pressure against the front wall. The distribution of the design earth pressure was trapezoidal.

3.2 Reinforced earth (method of using steel strip and friction)

A modern method of reinforcing earth was invented by Henri Vidal of France. His method was named "tèrre armée" in French. The first real retaining walls began to be constructed in 1964 and the first paper was published in 1966. A strip inserted in cohesionless soil restrains the relative movement of the soil by friction. This is the basic mechanisum of this method. Curved thin steel plates were laid horzontally one by one at the front wall of the retaining wall and steel strips connected to the plates to restrain the horizontal movement of the plates. A large retaining wall was constructed in southern France in 1968. Many researchers and engineers including engineers at the LCPC investigated both theoretically and experimentally. Later the concrete facing was replaced by the steel facing and the quality of strip was improved. This type of retaining wall has been used all over the world. Vidal's contribution to the area of earth reinforcement should be enormous.

Vidal came to Japan around 1966 and lectured to us at the Japanese Society of Soil Mechanics and Foundation Engineering. The Japanese National Railways (JNR) was interested in his retaining wall, and Hiroshi Uezawa of the JNR introduced his retaining wall in the journal of the Japanese Society of Soil Mechanics and Foundation Engineering (JSSMFE). Uezawa made a prompt report of his research work on the reinforced earth. Technical introduction on commercial base was completed, and an 18 m high retaining wall was constructed by the Kagoshima Toll Road Public Corporation, Kyushu. The author was asked to judge the construction of that high retaining wall in 1967. It was the highest retaining wall of this type in the world, it was said. The JNR decided to adopt it widely, and prepared standard for design and implementation. The author was chairman of the committee for that. A model retaining wall reinforced with geonets was placed on a vibration table to examine the stability during earthquakes, at the Technical Institute of the JNR. The JNR published a manual for the design and execution on the earth reinforcement including the reinforced earth in 1983. The Japan Road Public Corporation constructed a reinforced earth retaining wall at the Hokuriku Motorway at the suggestion of the author, in 1975. The Public Works Research

Institute (PWRI), Ministry of Construction, drafted a manual on reinforced earth retaining walls, and the Civil Engineering Research Center published a design manual to unify the design and execution in order to obtain a more reliable quality of the retaining walls.Many papers were written by many authors in the journals. A special volume for earth reinforcement was published by the JSSMFE, and Yoshiaki Hashimoto wrote a paper titled "Friction between soils and ribbed strips in reinforced earth walls". A book titled "Methods of reinforcing earth", was published by the JSSMFE in 1986, 14 % of the total 426 pages were allocated for the reinforced earth walls. The method of design against earthquake was described in this book.

Only examples of development in Japan are written here, but similar events occured in other countries.

3.3 Earth reinforcement with steel bars and anchor plates

The author was involved in countermeasures against landslide at the Narugo Dam in 1959. A small scale landslide was found at the left bank of the dam site. A tunnel was excavated horizontally, and the anchor concrete block was placed in a firm ground behind the sliding surface. Then a wire rope was attached to the block, and a concrete slab was made covering the surface of the sliding soil as shown in Fig. 4. Thus the movement of the slide was controlled. This was the origin of the earth reinforcement with steel bars and anchor plates. A high road embankment having 40 m in height and 1 : 1.5 in inclination was constructed at Kokanzawa of Sagami Lake, Kanagawa, in 1663. Artificial soft ground in the lake was strengthened by sand compaction piles, but the slope seemed to be unstable even by a careful compaction. Therefore a method of earth reinforcement with steel bars and concrete plate anchors were inserted into the embankment as shown in Fig.5. The

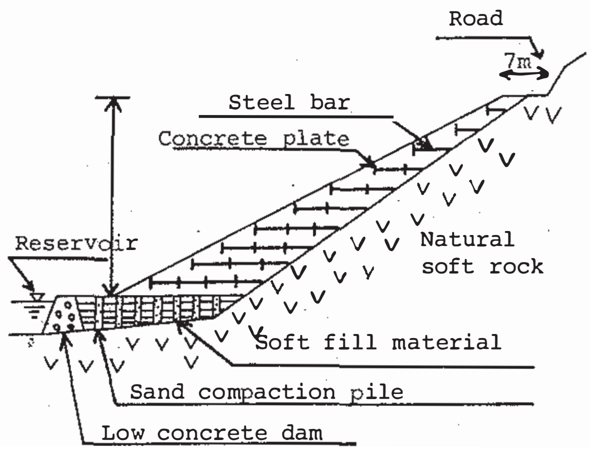


Fig. 5 High road embankment reinforced by steel bars with concrete plates, 1963

plates restrained the horizontal movement of the embankment body. Back of the steel bars were anchored in the rock by excavating drill holes if it was possible. It can be said that a combination of earth reinforcement and simple anchor was effectively used. Figure 6 shows a 20 m high embankment with the slope of 45° which was constructed by the use of this method in Toyama in 1982. The material of the slope was gravelly soil which collapsed during heavy rain.

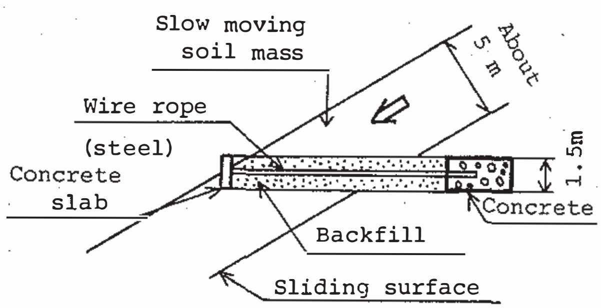


Fig. 4 Steel wire rope to check slow moving soil mass at Narugo Dam in Japan

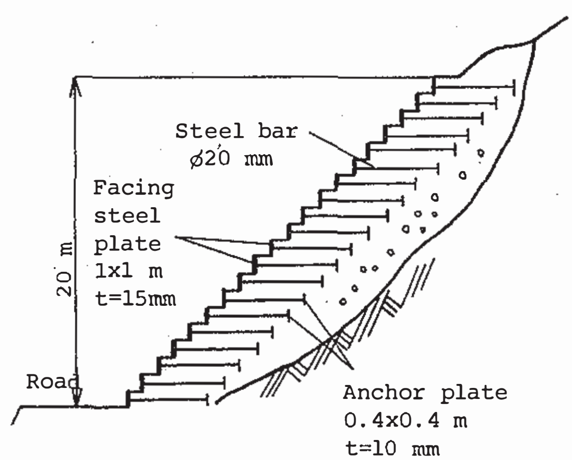


Fig. 6 Slope reinforced by steel bars with anchor plates

An experimental work aimed at applying this method to retaining walls was performed by the PWRI in 1965, but an actual retaining wall was not constructed. A high steel faced retaining wall was constructed by the author at the Noda Campus of the Science University of Tokyo in 1979. A 5 m high concrete and fabric faced retaining wall was constructed in 1980, and the earth pressure during earthquake time was measured with this retaining wall. A private company constructed a concrete faced retaining wall in 1983, and they constructed a 15 m high steel faced retaining wall for the JNR in Kyoto in 1985.

The steel bars with steel anchor plates were laid between the soft subsoil and the high embankment to prevent horizontal movement of the embankment at Hayashima Interchange in 1985.

The earth reinforcement method by the use of steel bars and plate anchors have advantages over that by the use of metal strips because the round bars are more resistant against rust, and because the plates restrain any kind of soils, even very soft clay or coarse gravel with sharp edges. Ordinary soils excavated at the construction site can be used without using sand from other places. Ordinary soils increase their strength by compaction, and moreover, the amount of reinforcements can be saved by using their characteristics of ordinary soils.

Strictly speaking the earth reinforcement method used for retaining walls with rigid facing may not be called an earth reinforcement method, but a wall between the earth reinforcement method used for retaining walls with rigid facing and other ordinary reinforcement method was removed since reinforced earth retaining walls with concrete facing appeared. Therefore, multiple anchored retaining walls having concrete facing can be regarded as a member of the earth reinforcement family.

Wu Xiao-Ming of China invented the retaining wall with concrete slab anchors independently around 1976, and many retaining walls of this type were constructed in China.

A sliding device between the wall and anchor rod considering settlement of backfill was invented in Japan and Prof. Masaru Ho.hiai et al made experiments for this type of retaining wall.

3.4 Retaining walls in the UK

Collin J.F.P. Jones wrote a book titled "Earth Reinforcement and Soil Structures" which was translated into Japanese in 1986. There are many different kinds of anchors in his book. R.T. Murray and M.J. Irwin wrote a paper concerning the cheapest type of anchors. They are a double reverse bend of "Z" shape with a short length at one end, and triangle shape and incorporated a short length of weld to prevent the anchor being distorted when subjected to tension forces.

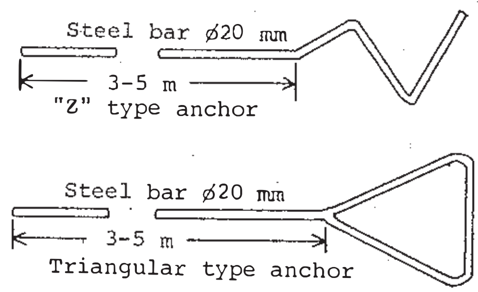


Fig. 7 Types of TRRL anchors(after Jones)

3.5 Reinforcement of natural ground

3.5.1 NATM

NATM stands for New Austrian Tunnelling Method. This name seems to be used in Austria, Japan and some developing countries. The principle of this method is to protect the inside wall of the tunnel by positively utilizing the arch or ring action of natural ground with rockbolts and shotcrete. There are 3 main points with NATM. They are rockbolts, shotcrete and measurements of deformations. The first record of rockbolts was of that A. Bush used them at the coal mine at Frieden in 1912. The rockbolts were used for reinforcing hard rock in the 1930's, and they came to be used even for soft rocks and hard soil. When they are used for soft rocks or hard soil, a drill hole in the natural ground is filled with cement mortar and a steel bar inserted into the drill hole. The number of cases to which this method was adopted increased since around 1950. This method began to be applied to civil works since L. v. Racewicz of Austria suggested that the rockbolts restrain natural ground around the wall of tunnel with a circular section to reduce the area of looseness. As for shotcrete, the first application of shotcrete to a tunnel was at the Maggia hydroelectric tunnel of Switzerland in 1951-55. It was found that the thin concrete layer had flexibility and behaved in harmony with the surrounding natural ground. L.v. Racewicz published a new method of tunnelling by writing a paper on the theme "The New Austrian Tunnelling Method (NATM)" from the November number of 1964 to the January number of 1965 of the Journal of Water Power. The NATM began to be used since around 1965 in Japan. The rockbolts were of the expansion type and used experimentally for the inclined shaft at Yoshioka in Hokkaido, which was a part of Seikan Tunnel of the JNR. An article concerning rockbolts and the shotcrete was included in the standard tunnel specifications by the Japanese Society of Civil Engineering. A genuine NATM was applied at Nakayama Tunnel of Jyoetsu Shinkansen by the full use of the rock-bolts, shotcrete and measurements of deformations in 1976, and the technology of this method was completely established. This method was used for road tunnels since 1978. The shield tunnelling method had been used for tunnels in cities to avoid the ground subsidence caused by tunnelling works. The technology of NATM was improved by the use of auxiliary measures such as steel supporting members, mini-pipes, simple steel sheet piles, deep wells, etc. The amount of land subsidence caused by tunnelling works was therefore reduced remarkably. The cost of tunnel construction was reduced by using a more economical NATM than the shield tunnelling method. Even the depth of the tunnel is small, the thin layer above the tunnel is reinforced by the vertical rockbolts or concrete piles with reinforcements. As the result, the ground subsidence is kept to a minimum. The soil constants are determined by the soil survey before the design of the NATM tunnel. Deformation and the factor of safety against rupture of the ground are calculated by the use of the FEM etc. The behaviour of the earth is measured by the use of extensiometers, earth pressure gauges, pore pressure meters, reinforcement gauges, etc. as the construction work is carried out. The amount of rock-bolts and supporting members are adjusted by interpreting the results of measurements. Kuriyama Tunnel of Narita Shinkansen, Kokubu River Tunnel, and Washuzan Tunnel of the Honshu-Shikoku Connecting Road are remarkable examples of the NATM tunnels, where the loose sandy soils of thin layer cover the tunnels.

3.5.2 Reticulated root piles

Reticulated root piles are a method of reinforcing natural earth on the basis of principles similar to the reinforced concrete, and developed by FONDEDILESPA of Italy. A similar method has been used to reinforce old buildings of brick and stones since long ago in Europe. The method was first applied to reinforce a natural slope in the USA in 1975. The first paper was published in 1978. The pile is composed of cement mortar and steel reinforcement, and is inserted into a hole excavated in the natural earth. This method was introduced to Japan in 1980. When a shield tunnel was excavated near an observatory in Tokyo, the foundation was consolidated by the use of the reticulated root piles. The observatory did not sink or tilt. The success of this work proved the effectiveness of those methods. Research work has been carried out in connection with the real construction work. Figure 8 shows a sketch of the cross-section of the reinforced slope for field test by Prof. T. Matsui et al.

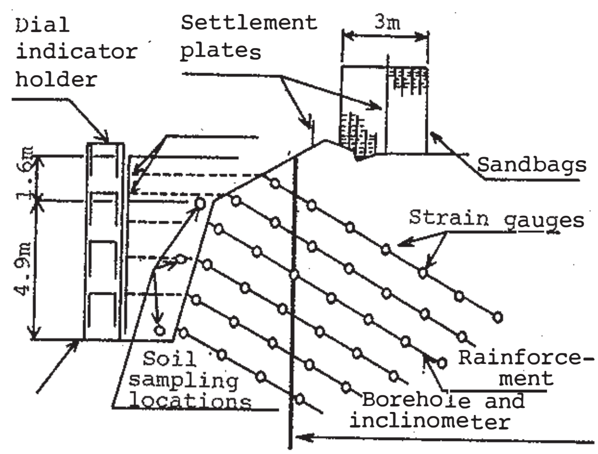


Fig. 8 Plan of the reinforced slope (after T. Matsui et al.)

3.5.3 Excavated slopes reinforces with steel bars

It seems that the method of reinforcing excavated slopes with steel bars was derived from the rockbolting method for tunnels. This method is used in both Europe and Japan. There are several methods for driving steel bars into the natural earth. Method of driving steel bars by breaker, method of making holes by a simple drill and method of making holes by drilling machine, etc. It is very common to drive deformed bars of 25mm in diameter and 3 m in length without using expensive drilling machine. The ordinary steel bar method differs from rockbolting, because it does not use any grouting. The former is cheaper than the latter, but the pullout resistance increases if the grout is carried out through a small hole in the steel bar. The slope excavated from the top of the ground is reinforced by steel bars step by step before the newly excavated portion of the slope becomes loose as time passes. Slopes are inclined more or less in general, but there is an example of vertical cut in uniform loose fine sand of 19 m high. However rockbolts 25 mm in diameter and 4 m in length were used in this case (Fig. 9).

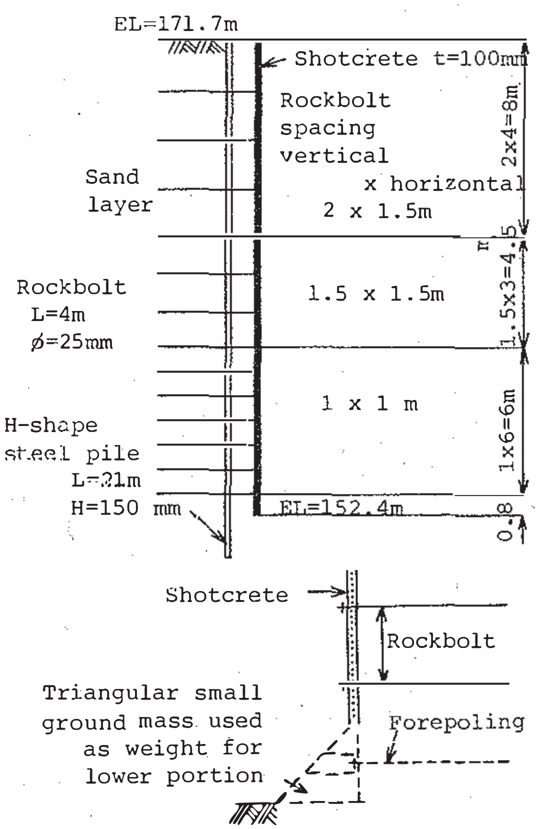


Fig. 9 Silty sand vertical cut reinforced by rockbolts (after Kitahara et al.)

Steel bar reinforcements have been used widely by the Japan Road Public Corporation and case records were analyzed by Teruki Kitamura et al in 1985. It was applied most frequently to soft rocks or hard soils. The most common lengths of steel bars covered from 2 to 4.5 m and the direction of driving bars was mainly downwards. The most common spacing was 1 to 1.75 m.

3.6 Other steel materials

There are many reinforcing materials using steel. One example is called "expand metal", which is perforated and expanded metal. This material is used to reinforce the earth. Steel bars for reinforced concrete are used to reinforce the earth in the form of lattice. Steel frames with rock inside is widely used as a Sabo dam (check dam) in Japan.

4 GEOTEXTILES AND RELATED MATERIALS

4.1 Geotextiles

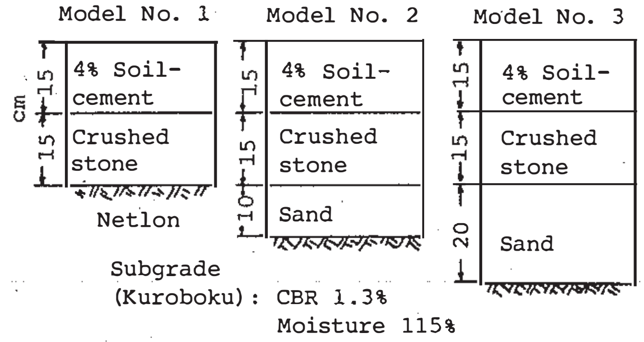
The first geotextiles used for the purpose of reinforcing earth were woven textiles. A high tide occured in the North Sea in 1953, and the flood water covered 1,5000 km^2 of land and about 2,000 people were killed in the Netherlands. The Dutch government made the Delta plan, and decided to reconstruct the broken dikes over 22 years. Geotextiles were adopted instead of traditional fascines, because the former was difficult to fabricate in a short time. Nylon bags were used at the begining. The materials, machines, and methods of execution were revolutionally improved year by year, and total area of geotextiles used reached 10 million m^2 by the middle of 1980.

The PVC monofilament woven geotextile was first used at the base of the riprap under the sea dikes of Florida, USA, in 1958.

The woven vinyl fabric was first used instead of straw bags in early 1950's in Japan, but it was not widely used. A high tide accompanied by the Ise Bay Typhoon hit Nagoya Area, and about 5,000 people were killed by the sea water flooding through the broken sea dikes. The woven geotextiles were laid under the riprap for the purpose of separation and reinforcing. It is interesting that both the Netherlands and Japan used very expensive material for the reconstruction works. A new construction material may receive an opportunity to be used in times of emergency.

Ryuji Fukuzumi was the first person who used the woven geotextiles commercially to reinforce very soft clay ground along the sea coast. His report said, "The author, from around 1964, had been studying the application to civil works of synthetic chemical fibers. The first to be developed by the author was the mat method. This consisted of taking two

(a) Simplified model pavement sections



(b) Relation between number of load applications and surface deflection for model pavement. Unimmersed case.

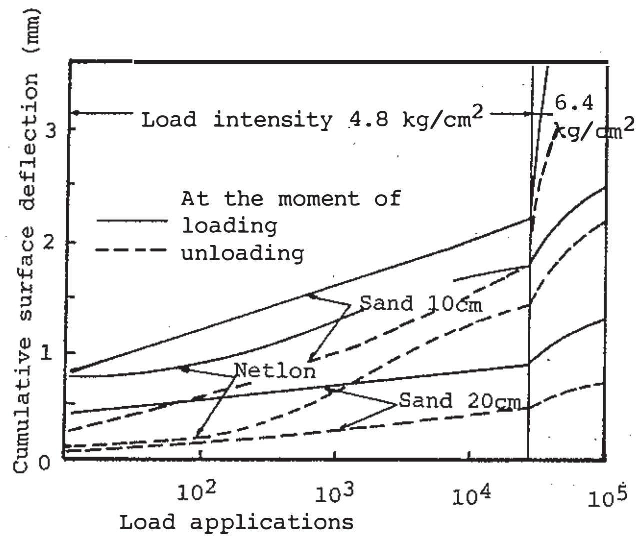
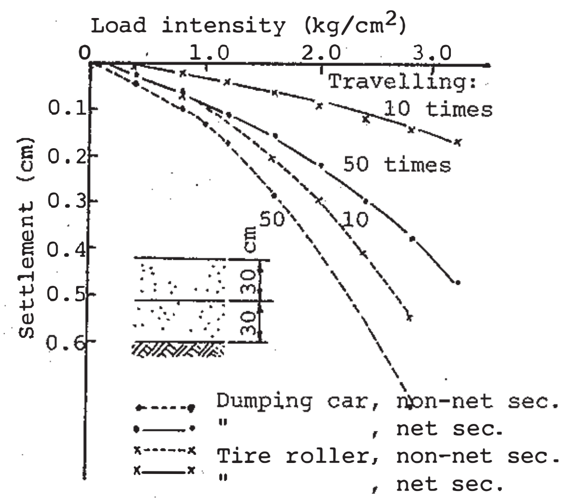
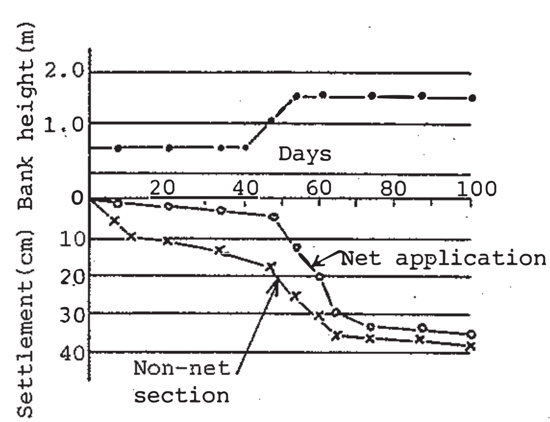


Fig. 10 Test results on structural effect of restraint layer on subgrade of low bearing capacity in flexible pavements (after T. Yamanouchi)



(i) The case of 60 cm thickness

(a) Results obtained from the plate bearing tests.



(b) Settlements observed using settlement meters.

Fig. 11 Test results obtained from test road for the work of Tohoku Expressway (after T. Yamanouchi) sheets and sewing them together to make tubes. Sand was packed in these tubes in succession to make a mat. It was found there was a considerable problem about this method being practical from the standpoints of efficiency and economics.

In 1966, at the time of construction of the Sakai Factory of Ube Industries at reclaimed land, good-quality soil was directly spread as a part of surface-layer treatment work, but the spread soil sunk to the bottom of old sea bottom and the project had to be stopped for practical purposes. Application of the mat method was therefore planned, but since the area was as much as 50,000 m^2, while moreover, the construction period was short, the sheet method was thought of counting only on tensile strength, one of the effects of the mat method. --- Sand of thickness of 35 cm was banked, and on top of this good quality soil of 35 to 65 cm was spread. --- at the sheet method area using sheets made of vinylon of tensile strength of 3 kg/3-cm width, even settlement was seen as a whole although there were some differences, and stabilization was achieved. --- At the stage of the test works, a Japanese patent was applied for in June 1966, which patent was granted in April, 1971.".

Shunske Sakai et al invented a method to reinforce geotextiles to cover soft ground, and prevent the swelling caused by pushing the filling soils by bulldozers.

This is a case of embankment using a weak cohesive soil with a high moisture content, but Toyotoshi Yamanouchi invented a method to reinforce the soil by laying a drain. The drain is lime covered with cardboards made of polyvinyl chloride. The method is called the "multiple-sandwich method".

4.2 Geonets

Geonets were invented in Britain to meet new demand. F.B. Mercer, inventer, wrote the following in his paper. "This process is a method for integrally extruding polymetric mesh structures in one step, from the molton polymer to the finished product, through a multiplicity of manufacturing steps. In the production of Netlon, molten polymer is extruded through two sets of opposing die orifices which are relatively displaced transversely to the direction of extrusion. The intersections are created when the orifices are in register and the mesh-forming strands are divided from the intersections with a shear action as the dies move from the registration position. Geonets (Netlon) was invented in 1958. Prof. Yamanouchi carried out laboratory tests for geonet, and used it at the real construction site. He recognized that the geonet had the effect of interlocking and abutment of grids for stabilizing soils, compared with plane faced materials such as geotextiles. His paper was published in 1967. As the results of model tests of static and dynamic loading, he reached the following conclusions.(Fig. 10).

"From the above-mentioned tests it has been proved that pavement restrained by such a low pressure polyethylene net as Netlon is strengthened in structures under repeated loading. The direct effect of restrained layer in this case is as if the subgrade soil itself underwent improvement, and the author believes that the effect may be applied to pavement design by using the equivalent bearing capacity of subgrade or equivalent depth of sand blanket." He performed a static and dynamic tests to check the effect of the geonet for stabilizing soft ground, and obtained the following results. "As a result of the forgoing experiments, it has been shown that improvement of bearing capacity of soft soil can be effected by resinous net for static loading, but not always for repeated loading. These conclusions are thought to suggest the proper use of the net method, as well as proving useful for interpreting some of the field trials that have been already carried out." As the result of laboratory tests, the use of the net was useful only for the static load. However, the results of field tests proved that the net was effective under dynamic loading. Many tests were performed to construct the Tohoku Motorway more economically, and tests were made for resinous net that was selected as one of the promising materials. The test results were summarized as follows by Professor Yamanouchi. "This road test showed the additional informative data even in Fig. 11 (a) in which the effect of a resinous net application was distinctly advantageous for the case of placing it in a relatively thin sand layer. This result is not unlike that obtained from a model test by the author as noted in the introduction in this paper. Moreover, the test gave the significant information shown in Fig.11(b) that the settlement after a long time apparently become close to the settlement in the untreated section. This means that resinous nets elongate to follow the settlement to the bank in some cases."

Reclaimed land with soft clay cannot be

filled up directly with good soils. It was recognized that the surface of the soft ground could be strengthened by using geotextiles but they were occasionally broken during construction. Therefore, the method of strengthening the geotextiles by covering rope nets, and filling with a layer of sand by the use of sand pumps or pipe lines was adopted. Methods of analysing the rope net method were presented by several authors. Shimizu proposed to use catenary taking into account of the strength of the ropes.

When the circumstances, which demand some new methods, are reached, many persons invent new good methods independently and almost at the same time. The use of nets for the purpose of strengthening earth was also the case. S. Morita used steel nets at the Miike artificial island in 1949, and Kazuo Horimatsu of the Japanese National Railways (JNR) used fish nets to reinforce an embankment soil in 1964, and received a patent in the name of "Reinforcing body embedded in soil structure". He also received patents in following years and now has a total of 21. He also wrote many papers. Komei Iwasaki and colleagues of the JNR succeeded to reinforce embankments with newly developed resin nets in 1965. This was the first field test to strengthen an embankment by placing nets on a soft subsoil in Japan. The purpose of the test was to evaluate several methods of improving the soft subsoil for the vibration of trains. As for the effectiveness by static loading, there were 5 check points.

Initial settlement: average.
Long-term settlement: fairly good.
Lateral movement: excellent.
Increse of strength for subsoil: average.

As for the effectiveness by dynamic loading, there were 4 check points.

Up and down movement of the embankment: not clear.
Left and right movement of the embankment: fairly good.
Movement of ground near the foots of the embankment: bad.

In conclusion, the use of net was effective for vertical settlement and lateral movement, but exaggerated the vibration of the neighboring ground.

The JNR constructed 2.5 m high embankment on a soft ground, and examined the methods of safe execution, reducing the permanent settlement and the unfavorable effect of the old embankment at the time of increasing number of tracks. The methods tested were sand drains, lime piles ("chemico piles"), sand compaction piles("composer"), gravel piles, and resinous nets. In conclusion, the deformation of the ground was very little because the net distributed the local load over the wide area and the lateral movement of the ground was also small. The total amount of settlement and the increase of strength of subsoil were same as in the case of no net.

4.3 Geogrids

Mercer of the UK invented the high strength polyethylene net and also invented the extended polymer grid which had an extremely high elastic constant ("Tenser"). The material was imported to Japan and research and technical development were carried out for it. There were many examples of applications. The first report on the use of a geogrid for the purpose of reducing earth pressure against a retaining wall was the one by Naozo Fukuda et al. An example of use for the purpose of preventing unequal settlement was reported by Katsuyuki Kutara. An example of the use for reinforcing a long slope was reported by the Japan Road Public Corporation. An example of the use for constructing a vertical wall was reported by Kagoshima Developing Association in Kyushu. The two axially extended polymer grids were laid over the pile nets. The polymer grid has been used in the form of a mattress for foundations of roads, embankments, buildings, etc.

The micro-net was invented in the UK and introduced in Japan, but is not widely used at the moment.

4.4 Vertical drains

O.J. Porter of the US invented the sand pile around 1935. Walter Kjellman of Sweden invented the cardboard wick to drain saturated weak subsoils for the purpose of consolidation. A heavy machine was constructed to drive many vertical drains into the subsoil at Arlanda new International Airport around 1950. The machine was sold out to the Franky Pile Co. after completing the soil improvement of the airport. The author helped the introduction of the technique for cardboard drains into Japan in 1963 and sixteen sets of heavy machines were manufactured by a Japanese company after improving upon the original Swedish design. The Japanese machines were used at the reclaimed land for NKK in Fukuyama City. The report from this construction work was made by Yoshiharu Watari. Theory, testing methods such as permeability test, estimation of effective diameter and the method of design proposed at that time are still used. Some of the machines constructed in Japan were exported to Europe. A method of soil improvement, which uses both cardboard drains and a vacuum, was invented by W. Kjellman. This was applied to consolidate soft tailings with fine grained coal at Fukuoka City. Thus the methods born in Sweden were applied to actual large construction sites and technically developed to a remarkable degree. The cardboard material was made from pulp in Sweden. Geotextiles and plastics began to be used instead of the pulp and it is said that high quality drain materials are produced by Japanese companies. When the vertical drains were driven through geotextiles laid on the soft subsoil, the geotextiles were broken, and the soft subsoil blew up through the broken parts. This trouble was overcome by the use of the rope net method. The big national project for Kansai International Airport is now being implemented. The thickness of the soft ground is about 20 m, and the water depth is about 20 m, and the height of the embankment 25 m. Many boats equipped with a huge machines which can drive 8 sets of drains at the same time are working effectively. About 300 thousand vertical drains will be driven in a very short period of construction.

4.5 Texsol

A method of reinforcing sand by mixing long continuous yarns was invented in France around 1979. E. Leflaive who invented the method said that he obtained the hint from the roots of the plants. This method was patented by the French government. It was introduced to Japan in 1987, and experimental works have been carried out extensively.

4.6 Method of analysis

Method of analysis has been developed by many engineers. The first group assumes a rupture surface. The reinforcing material across the surface is pulled and the tensile force on the material is compared with the tensile strength of the material. At the same time, whether the material is pulled out after the friction between the soil and the material exceeds the ultimate value of the friction or not. The second group divides the whole body into small elements of soil and reinforcing material. The relationship between stress and strain is calculated by the FEM, etc. The deformation of the whole body and the possibility of rupture are examined while stress and strain is accumulated on the elements. Detailed discussion on this point is avoided because of space limitations and only the papers by Fumio Tatsuoka et al are introduced here, because they are important but not very well known. Everyone believes that the reinforcing materials are effective, because their Young's moduli are much higher than those of soils, but their Poisson's ratios are also important. The lower the Poisson's ratio the better. The Poisson's ratio of nonwoven geotextiles is zero according to the plane strain test by Tatsuoka et al. If nonwoven geotextiles are inserted into an embankment of cohesive soil, the soil around the geotextiles will not be saturated. It means that the soil maintains suction, which prevents the reduction of strength of the soil. This is a great merit of using nonwoven geotextiles for the purpose of reinforcing embankments.

Analysis of deformation of geotextiles in earth was performed by using the FEM. The model proposed by Kutara et al is shown in Fig. 12 as an example. The geotextile was replaced by a plane truss element, and the joint elements were placed on discontinuous planes between the geotextile and soils respectively. The plane truss elements were connected with pins. Figure 13 shows the deformation characteristics of the joint element. It is assumed that the square elements of soils cannot resist tension. The pull out test was performed to determine the constants involved. A large scale model test of a retaining wall reinforced by geotextiles was performed, and the test results were compared with those of analysis.

There are a dozen centrifuge apparatuses in Japan. Those are used for analysing behavior of soils reinforced with geotextiles etc. The mechanical behavior of reinforced ground with high elongation characteristics was analyzed by Saito et al. As the result of centrifuge testing, it was recognized that the geotextile restrained well deformation near the ground surface. Friction between the ground and the geotextiles played an important role. Deformation in the ground caused by loading was reduced by the geotextiles, and a drain effect of geotextiles was observed.

The stress-strain relationships of soil structures changes with construction methods, non uniformity of soils, flexibility of supporting structures,

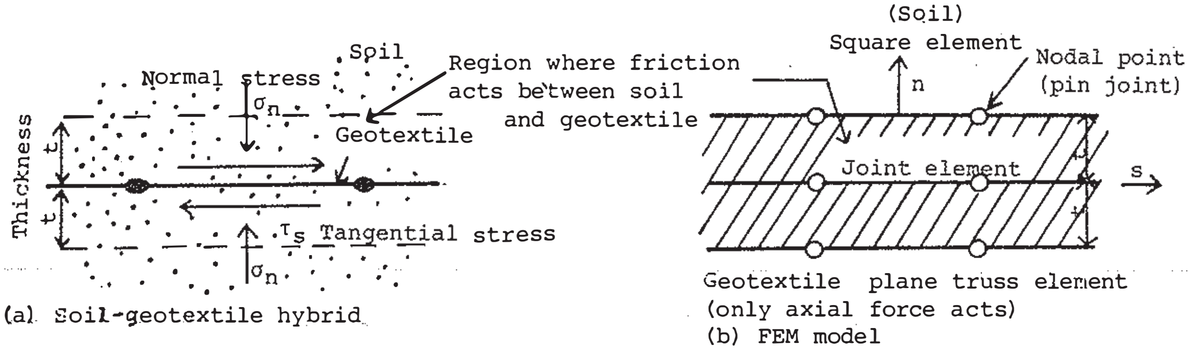


Fig. 12 Model for FEM analysis (after K. Kutara et al.)

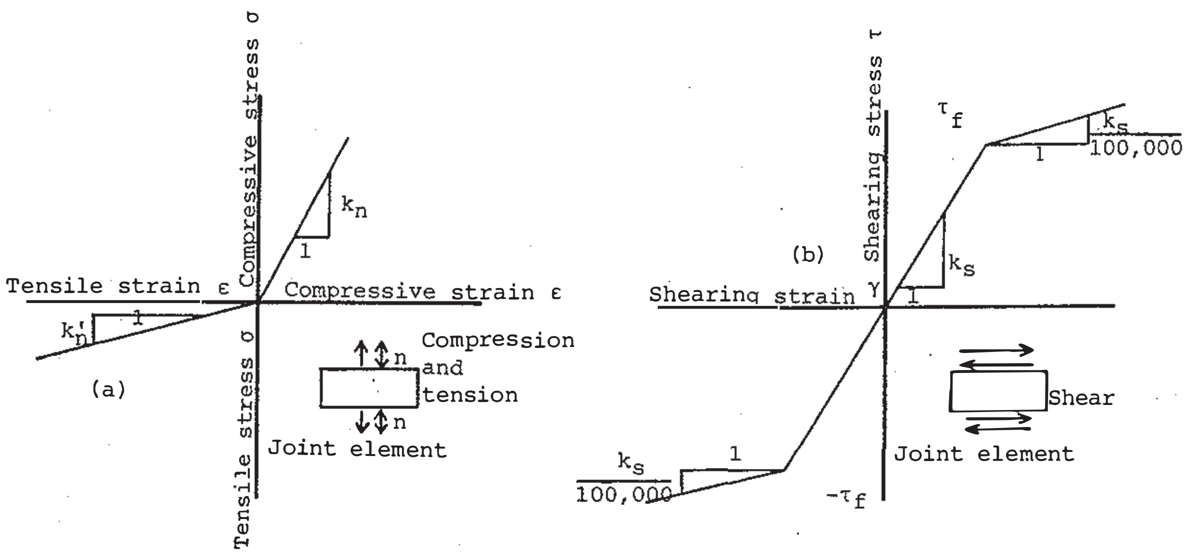


Fig. 13 Deformation characterics of joint element (after K. Kutara et al.)

foundations, percolating water from rain and snow, earthquakes, etc. Soil structures with reinforcements are more complex than those without reinforcements and so the accumulation of well documented case records is very important so that there is not only analysis to rely upon to make a safe and economical design.

4.7 Resistance against earthquake

Severe earthquakes occur frequently in Japan. Therefore, earthquake resistant design should be applied to the earth structures with reinforced materials in Japan. Some papers presented to the 3rd I S in Vienna discussed the earthquake resistant design using the conventional seismic coefficient method. Geotextiles are effective for preventing the liquefaction of saturated sands during earthquakes. This fact was revealed by Y. Mochizuki et al. The reinforcing effect is greater in the case of placing materials to direction of principal stress. If the reinforced materials are placed in the other direction, the reinforcing effect depends on the stiffness of the reinforcing materials.

Small scale shaking table test for the embankment reinforced by geotextile were conducted by Y. Koga et al. Various parameters such as the length of the reinforcements, the number of reinforcing layers, the slope of the face and the sort of the reinforcing materials. As the result, the reinforced part was acted as one block and the block resisted to the earth pressure like the gravity-type retaining wall. Figure 14 shows some results of the test. The model shaking table test of geotextile reinforced embankments on inclined ground was

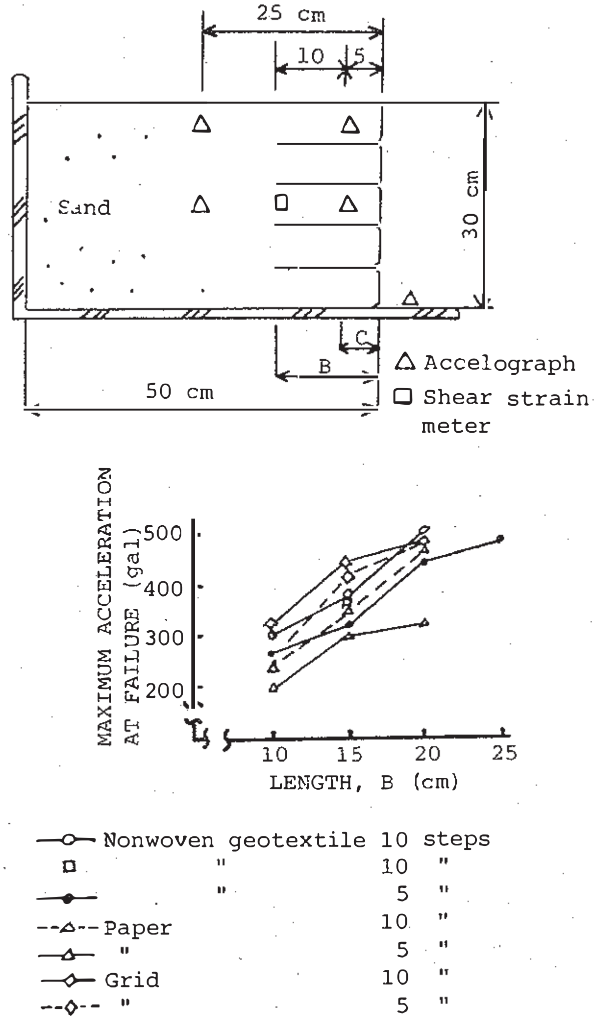


Fig. 14 Model shaking test of geotextiles reinforced embankment (after Y. Koga et al.)

conducted by Y. Koga et al. As the result, it was revealed that earthquake resistance increases when geotextiles are thickly included and when geotextiles with large stiffness are used, and the slope surface is rolled up with geotextiles. Stability analyses were also performed.

4.8 Resistance against heavy rains

Resistance against heavy rains is important in areas which have heavy rain, because embankments and retaining walls may collapse during heavy rainfall. Prototype experiments were performed out of doors. Large scale model tests applying artificial rainfalls have been conducted by the research group including the Public Works Research Institute, Ministry of Construction (PWRI) and the private companies since 1985. Figure 15 shows one example of the large scale model test. The total amount of rainfall was 420 mm over 3 days. The saturation ratio and the deformed surface after the test are illustrated in the figure. The tensile strains are less than 1 %, which is much small compared to the strain at failure of 10 % of the polymer grids. Erosion gradually occurred in the surface soil between polymer grids. K. Kutara et al investigated the method of protecting slopes by the use of polymer grids while H. Miki et al performed the test using the embankments reinforced by nonwoven geotextiles having two different thicknesses. Only the thicker of the two was effective as the drainage system.

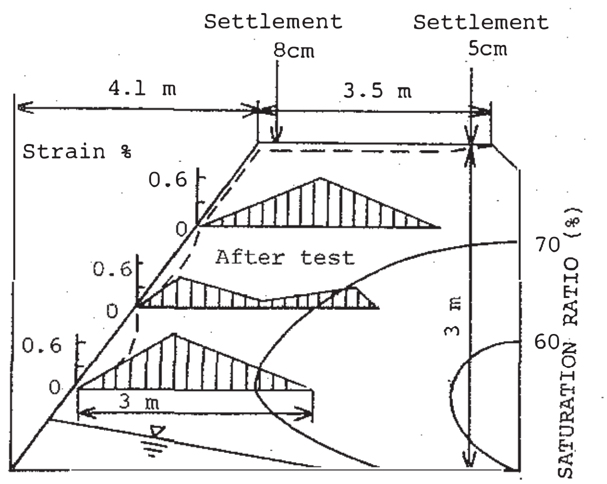


Fig. 15 Settlement, strain and saturation ratio after 420 mm of rainfall(after H.Miki)

5 CONCLUSIONS

Methods of soil reinforcement have been used in the west and east since very long ago. Methods of soil reinforcement using the modern materials such as steel and geosynthetics are made remarkable progress since the 1950's. Vidal's invention of reinforced earth and the development of the petrochemical industry had great influence on the promotion of these techniques. Many of the inventions and developments had been achieved in the west, and transfered to the east. However, some of discoveries and improvements were made in the east and some of them were developed remarkably through the extensive application to the real construction works. In this paper, the situation in Japan was emphasized, because the author thought that it may be necessary to introduce the papers written in Japanese and not yet public in other parts of the world. The content of this paper was divided into the two parts of steel and geosynthetics. At the end of this paper, research works for earthquakes and rains were described as it seemed that papers in this area have not been presented before in the west.

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