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Design assumptions and actual behavior in soil nailing

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ABSTRACT: Design assumptions and actual behavior in soil nailing are reviewed with respect to failure and deformation modes of nailed slopes. First, failure modes assumed in the present design methods and those actually observed during construction are presented. Secondly, deformation modes and mobilized nail force are described schematically, and discussed in relation to the findings obtained in current research works.

1 GENERAL REMARKS

The soil nailing practice seems to go ahead of the theory on the reinforcing mechanism as is often the case with other practical techniques in geotechnical engineering.

The soil nailing is one of versatile techniques to reinforce in-situ soil, thanks to its simplicity and flexibility in execution works. This technique has been used to stabilize both natural and steep cut slopes on small to medium scales. In urban areas the technique has also been used to construct temporary retaining structures to support the ground close to neighboring structures that are sensitive to deformation with appropriate measures to reduce ground movement.

As for the design some well organized recommendations and technical documents have been published based on the findings from research works and practical experiences gained for the past decades. However, in the present design methods, which are all based on the limit equilibrium stability analysis, the working principal of the nailing technique as passive reinforcement is not considered in an explicit way. Important subjects that cannot be solved by the limit equilibrium based analysis include evaluation of 1) deformation of nailed slope, and 2) soil strength and nail force mobilized in service in relation to those at failure. Durability of reinforcement required for long term stability of nailed slopes and preservation of environments are also important issues.

2 FAILURE MODES

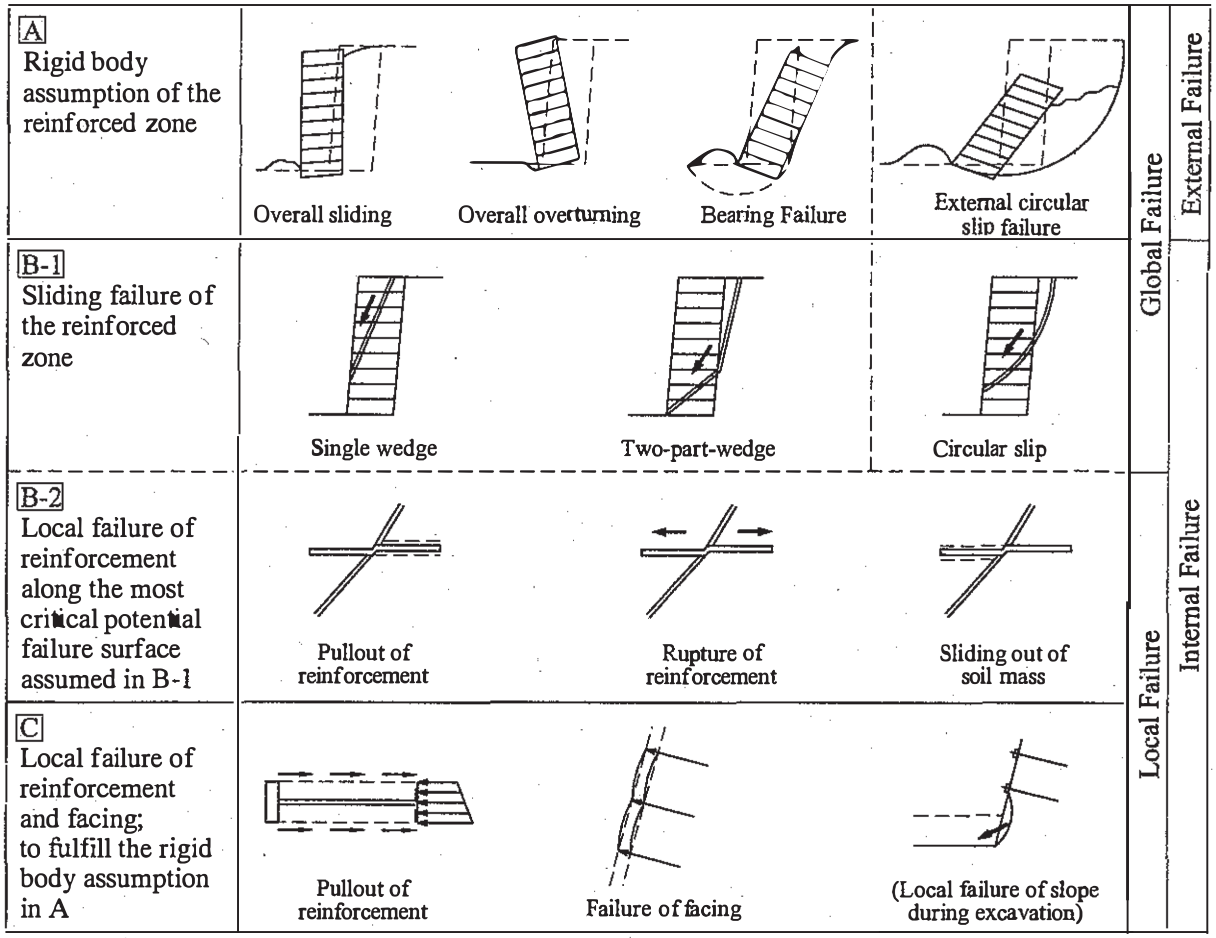
2.1 *Failure modes assumed in design*

In routine design, the stability of nailed slope is analyzed by the limit equilibrium method as for reinforced backfills. The Working Group for Design in "Research Committee on Reinforced Technology for Natural Slopes" (1996) summarized the design methods presently used in Japan. Table 1 shows possible failure modes of nailed slope assumed in design procedures. They are roughly classified into three groups with respect to external or internal failures, and global or local failures.

Group-A assumes a rigid reinforced zone to examine external failure modes with respect to sliding, overturning, bearing and circular slip failures likewise for a conventional retaining wall. For Group-B, the global stability is examined on internal sliding of either circular slip, single-wedge, or two-part-wedge failure (B-1). The local stability of reinforcement is examined along the most critical potential failure surface assumed in B-1. The local failure modes are pullout and rupture of reinforcement, and sliding out of the soil mass in the active zone (B-2). Group-C includes local failures of reinforcement and facing, which are examined based on the local equilibrium to fulfill the rigid body assumption in Group-A.

It is difficult to evaluate appropriately the density and layout of nails when the whole reinforced zone is assumed to behave as a rigid body (Group-A). In the majority of the design methods, therefore, Group-B is basically adopted to examine both global and local failures though Group-B covers part of Group-A. Among the external failures in Group-A, the circular slip failure is mostly examined as

Table 1 Failure modes assumed in the present design for nailing (Revised RCRTNS, 1996)



required depending on geological and loading conditions.

2.2 *Adopted design methods*

According to the fact-finding on application of soil nailing conducted by Japan Highway Public Corporation (Mouri et al., 1993), different types of design methods had been adopted as shown in Fig.1. It is seen that the single-wedge failure was adopted in a half of the total cases while the circular slip failure was adopted in 14 %. The empirical design method, which specifies a standard layout of nails to prevent relatively shallow failures without any design calculation, was adopted in approximately 20 %. This tendency may somewhat reflect the fact that the majority of collected cases were the application to rock slopes.

2.3 *Patterns of collapse actually observed*

The construction procedures of nailed slope involve a critical phase with respect to local or global stability. The Working Group for Execution in

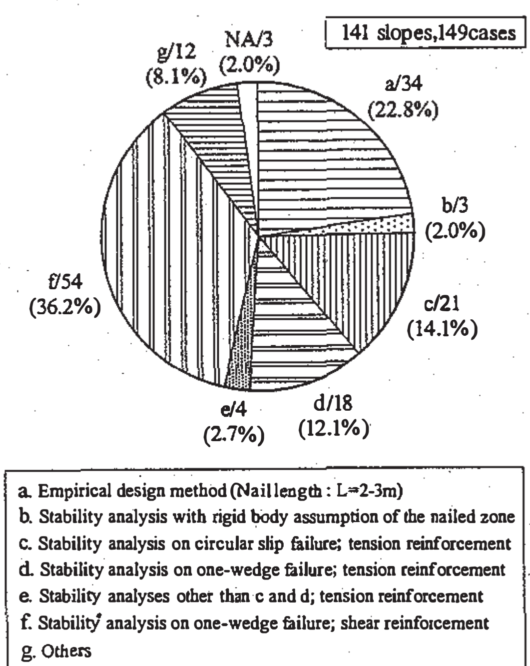


Fig.1 Adopted design methods (Mouri et al.,1993)

"Research Committee on Reinforced Technology for Natural Slopes" (1996) analyzed 1) typical failure patterns which have been observed so far during construction as illustrated in Fig.2, and 2) the probable causes for these failures as listed in Table 2.

It is considered that most of collapses occurred due to unexpected geological conditions and misjudgment on execution procedures. The overall sliding of a slope seems to have occurred either along failure surfaces that were deeper than the most probable potential failure surface predicted in design (Failure pattern-4), or those located at depths exceeding the limits of application of soil nailing.

However, the number of such external failure as above is limited. Most of the failure occurred either along shallow failure surfaces within nailed zones (Pattern-2,3), or in shallow zones which had been exposed without nailing or shotcreting after excavation below the nailed zone (Pattern-1,2,3).

Table 2 Causes of failure (RCRTNS, 1996)

Cause of failure		Failure Pattern *	(1)	(2)	(3)	(4)
Geological Conditions	local lack of cohesion of soil		○	○		
	ground water		○	○		
	misjudgments	in-situ soil strength		○	○	○
		in-situ pullout force			○	○
	unexpected conditions	deeper failure surfaces			○	○
		sliding along interfaces			○	○
Design Analysis	insufficient nail density			○	○	
	insufficient nail length				○	○
	insufficient pullout force				○	○
Execution Procedures	over excavation in height		○	○	△	△
	insufficient grouting	in drilled hole		○	○	△
		at the head	○	○	△	
	delay of fixing nail head			○	△	
	delay of shortcreting			○	○	○

*) Failure patterns (1) to (4) in the table correspond to those shown in Fig.2.

3 DEFORMATION MODE AND MOBILIZED NAIL FORCE

The actual behavior of nailed slope strongly depends on each specific condition at a site such as geological characteristics, gradient and height of slope, layout and density of nails, rigidity of nails and facing, external loading conditions and so on. We cannot precisely evaluate deformation of nailed slope either by empirical methods or numerical analyses considering various factors as mentioned above. Under such situations the practical approach to keep deformation below allowable levels would be monitoring field behavior with feed back to design procedures and using supplementary methods to reduce shear stress of soil and to increase rigidity of the reinforced ground.

3.1 *Schematical behavior of nailed slope during construction*

Fig.3 shows schematically the deformation modes of nailed slope observed during construction and in laboratory model tests. It is supposed here for simplicity that the ground is homogeneous and nails are relatively short compared to the slope height.

1) Global behavior of nailed slope

The stress release due to excavation causes deformation of the nailed slope. The loosened zone is characterized as induced higher strains. As excavation proceeds the loosened zone grows

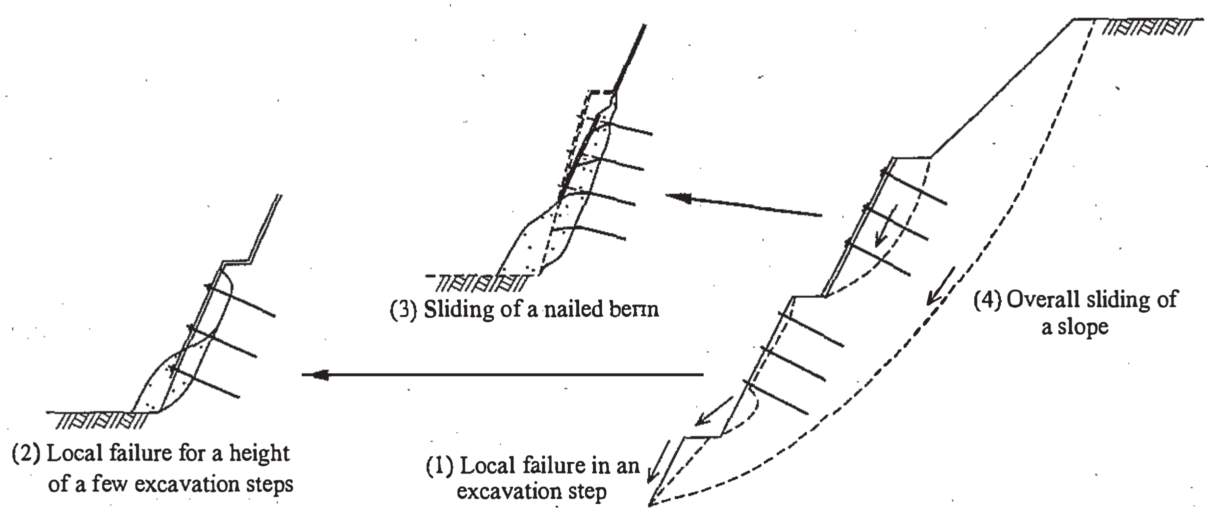


Fig.2 Typical failure patterns (RCRTNS, 1996)

backward to the backface of nailed zone. Due to the effect of reinforcement, soil strength that is larger than when the slope is excavated without reinforcing, is mobilized in the reinforced zone.

2) Displacement of slope face

Tilting is the most predominant displacement mode of nailed slope in the field. In this mode, outward horizontal and vertical displacements are maximum at the top of the slope, with the outward displacement occurring below the transient bottom of excavation. The slope tilting increases with excavation, resulting from deformation in both the nailed zone and the zone behind it.

3) Mobilized nail force

The tensile force in nail is mobilized by deformation of the nailed zone. The nail force at a certain level reaches its maximum after several excavation stages at depths below the level of the nail, whereas the slope deformation would continue by further excavation of the slope. Therefore, when the excavation is completed, the nail force at the lowest level is usually not largest, but may even be smallest. Then, the nail force would be redistributed by creep deformation in both soil and nails with an increase in the nail force at the lowest level.

Such a progressive nature of mobilization of soil strength and nail force as described above is not considered in usual design procedures. Rather, it is assumed that the design values of soil strength and nail force are mobilized simultaneously.

3.2 *Nail force distribution*

Along a given nail, the maximum tensile force T_{max} appears at a certain depth from the slope face (Fig.3). It is usually assumed that the location of T_{max} coincides with that of a potential failure plane (SCFNP, 1993). This assumption has been supported by a number of model tests in which slopes were forced to fail either by loading at the crest with a rigid platen, or by decreasing the soil

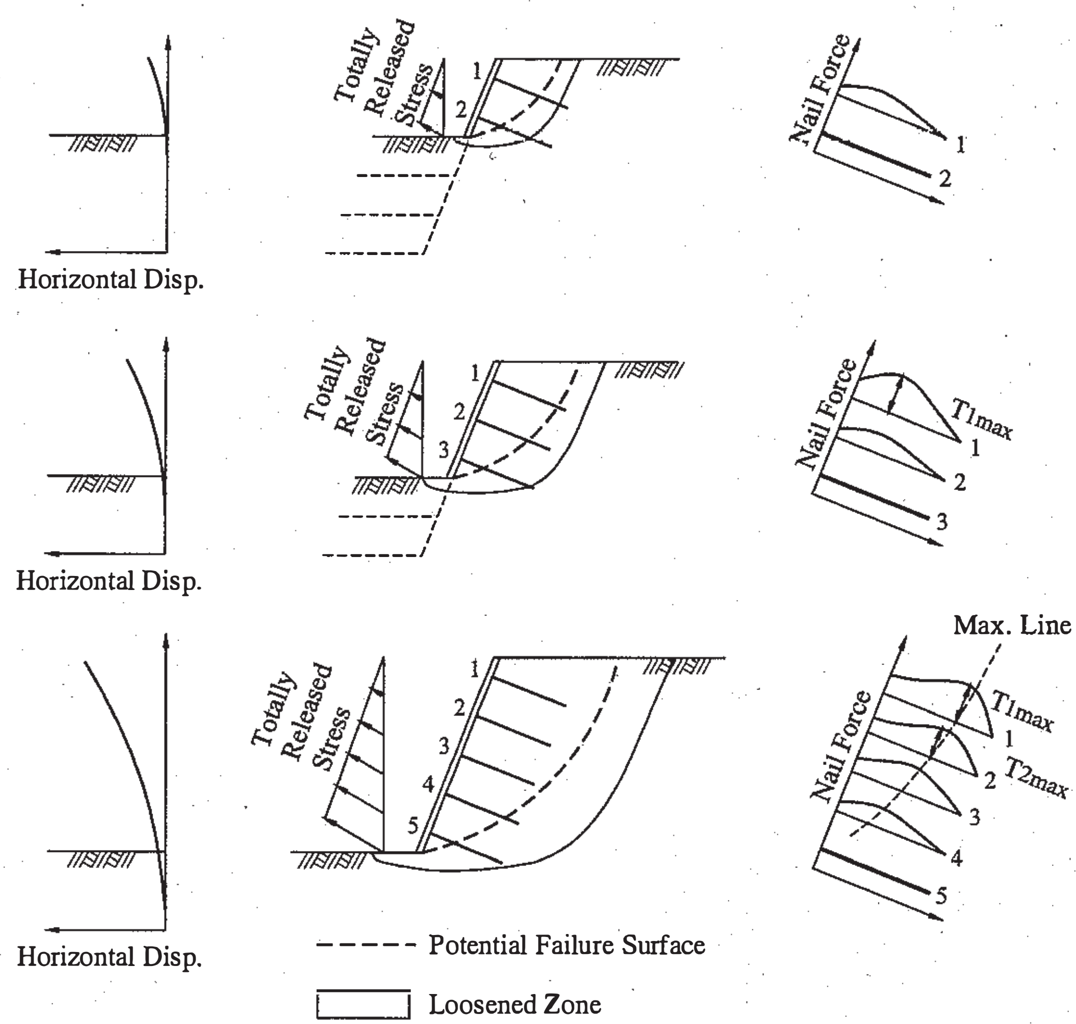


Fig.3 Schematic behavior of soil nailed slope

strength by water-saturating in 1 g model tests, or by increasing the soil weight in centrifuge tests. In some recent laboratory model tests in which the model slopes were brought to failure by decreasing the pressure on the slope face simulating the actual excavation process (Muramatsu et al., 1995), however, the location of T_{max} was found shallower than the failure plane. It was also shown that the nail force distribution be largely affected by the facing type; as the overall facing rigidity increases, the location of the maximum force T_{max} becomes closer to the slope face and the T_{max} value increases. According to this result and a number of field observations of full-scale behavior, in the design recommendation (JHPC,1995), different distributions of design nail force and T_{max} value are selected depending on the facing type.

When the direction of the potential failure plane rotates largely along a given failure plane, the effects of nail direction relative to the tangential direction of the failure plane where the nail is crossing the failure plane should be considered (Tateyama et al., 1993). The effects of the shape and dimensions of nails are also important, particularly for large-diameter nails (i.e., dowels). These factors affecting the mobilized nail force are not sufficiently considered in usual design procedures of soil nailing.

3.3 *Deformation modes far before and near or at the failure state*

As mentioned earlier, when a slope under excavation with nailing is far before the failure state, the most predominant deformation mode is tilting (Fig.4a). In many construction projects, the displacements at the top of slope are monitored during excavation, and judgments as to the current stability of the slope is made based on those observations. Based on the past experiences, it is usual that the procedure of excavation and nailing are controlled so that the outward lateral displacement at the top of slope be lower than 0.1 to 0.3 % of the current slope height.

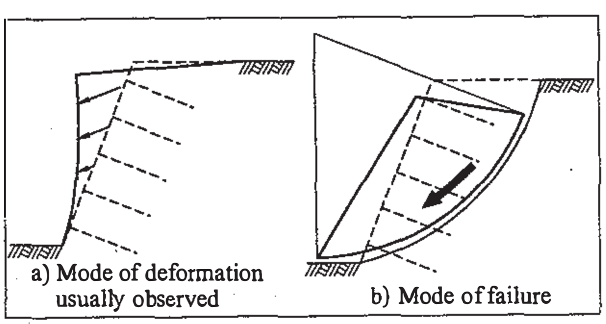


Fig.4 Modes of deformation and failure

On the other hand, the deformation mode when a nailed slope becomes near or at the failure state is often the rotational mode along a circular failure plane (Fig. 4b). In this case, as actually observed in a prototype slope (e.g., Aoki et al, 1996), the slope face near the slope bottom is pushed out largely around the slope toe.

The failure of both unreinforced and reinforced soil masses results from the progressive development of a shear band (or shear bands), which finally lead to an overall failure zone (or failure plane), or from the failure of reinforcement for a reinforced soil mass (e.g., Huang et al., 1990). Therefore, to simulate and analyze in a consistent manner both the deformation of a nailed slope during excavation and in service, at stages far from the failure state, and that near and at the failure state, a sophisticated numerical method such as the FEM analysis considering strain localization into shear bands is one of the promising methods (e.g., Kotake et al., 1996). In such analyses, a shear band width that is specific to the soil type concerned should be introduced. Further, more model tests bringing the slope to failure with careful observation will be required. It is expected that based on such researches as described above, the safety factor of a given slope can be estimated by monitoring displacements at the top of the slope during excavation.

4 PERMANENT NAILED SLOPES

Durability of reinforcement required for long term stability and preservation of environments are important issues for permanent nailed slopes.

1) Durability

There are few available information on long term durability of nails under actual working conditions, partly because of its short history.

Tayama et al. (1996) investigated the conditions of nails by sampling them by means of over-core boring from nailed slopes ten years after their construction. Though some nails exhibited partial corrosion due to insufficient grouting, most of the nails were in very good conditions. Considering the conditions of slope face that had been observed in inspection since their construction, they concluded that the nailed slope kept stability as had been designed.

Since the number of sampled nails is insufficient, more investigation will be required so as to specify design life of nails or nailed slopes based on actual performance. It should be stressed here that long term performance of nailed slope is closely related with execution control, especially in drilling and grouting. On the other hand, nailed slopes are relatively easy to maintain, compared with, for example, those stabilized by ground anchors. Though we have scarcely experienced rehabilitation of deteriorated nailed slopes, one of the proper methods may be restoring by additional nailing. Such a matter as mentioned above may be evaluated in terms of life time cost of stabilized slopes.

2) Landscape preservation

Besides the effects of facing rigidity on nail force mobilization as mentioned earlier, type of facing is also an issue on environments. Although a full-height rigid RC facing or lattice RC structure covering the whole slope face is better in stabilizing the slope, they would not be preferable for natural landscape preservation. One of the attractive methods would be the use of a facing having some degree of rigidity while allowing planting or vegetation (Horie et al., 1996).

CONCLUDING REMARKS

The nailing technique seems to be well-established in engineering practice. Currently the technique is often used in urban areas with appropriate measures to reduce deformation of the ground, being competitive to other types of earth retaining methods. Although deformation of nailed slope during cutting is the most important index to evaluate the slope stability, no reliable methods are available at present.

The seismic stability of cut slopes, being beyond the scope of this paper, is not usually examined in ordinal design procedures even in Japan. Seismic stability of reinforced soil structures was eventually highlighted after the disastrous Hyogo-ken Nanbu Earthquake. During the earthquake a number of nailed slopes were reported to have performed well (Tatsuoka et al., 1996). Reflecting this evidence, the nailing technique has been adopted for remedial and preventive works in many slopes. It is noted that aseismic design methods of nailed slopes should be developed taking into account its ductility as observed during recent large earthquakes.

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REFERENCES

(J) denotes in Japanese.

Aoki,H., Maruyama,O., Yonezawa,T., Taneda,N. 1996. Design Method of Reinforced Slope for Excavation (part2) -Measurement and FEM Analysis-, Symposium on Reinforcement of Natural Slopes, JGS, pp269-274. (J)

Horie,N., Kikuchi,H., Yamada,H. 1996. An application of composite long-fiber reinforced earth work method for stability and vegetation, Tuchi-To-Kiso, JGS, Ser.No.465, Vol.44, No.10, pp.33-34. (J)

Huang, C., Tatsuoka,F., Sato,Y. 1990. Bearing capacity of footing in reinforced sandy slope, Tenth South Asian Geotechnical Conference, Taipei.

Japan Highway Public Corporation, 1995. Guidance for Design and Execution of Cut-Slope Reinforcing Construction Methods (Draft). (J)

Kotake,N., Tanaka,T., Tatsuoka,F. 1996. Numerical simulation of plane strain compression failure of reinforced sand, Annual Conference, JGS, pp.2431-2432. (J)

Mouri,S, Tayama,S. 1993. Current application and subjects on reinforced slopes with steel bars, THE DOBOKU-SEKOU, Vol.34, No.7, pp39-46. (J)

Muramatsu,M, Sueoka,T, Tatsuoka,F. 1995. Reinforcing mechanism of soil nailing and effects of slope facing, JSCE, No.517/III-31, pp93-104. (J)

Research Committee on Reinforced Technoogy for Natural Slopes, 1996. Activity Report, Symposium on Reinforcement of Natural Slopes, JGS, pp1-191. (J)

Scientific Committee of the French National Project. 1993. CLOUTERRE: RECOMMENDATIONS CLOUTERRE, 1991 (Soil Nailing Recommendations 1991).

Tateyama,M., Tatsuoka,F., Kishida,H., Urakawa,T., Tamura,T. 1993. Consideration on reinforcing effect in bar like reinforcing members, Annual Conference, JGS, pp.2787-2290. (J)

Tatsuoka,F, Koseki,J, Tateyama,M. 1996. Performance of reinforced soil structures during the 1995 Hyogo-ken Nanbu Earthquake, IS-Kyushu '96 Special Report

Tayama,S., Maeno,H., Matsuyama,H. 1996. An investigation on durability of ground reinforcement technique, Tuchi-To-Kiso, JGS, Ser.No.465, Vol.44, No.10, pp.35-36. (J)