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Design of reinforced soil wall – Overview of design manuals in Japan

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ABSTRACT: SC3 members of TC9 Supporting Committee setup in Japanese Geotecbnical Society summarized the current state of Japanese design manuals for reinforced soil wall with considering the development of design code such as ISO, Eurocode and AASHTO. In the present paper, the authors introduce the current state and consider some task to establish the comprehensive design manual having accountability in order to keep up with the development of design code.

1 INTRODUCTION

Development of new reinforcing method and design manual has been an important task in the field of reinforced soil method. In 1990th, new design codes have appeared such as Eurocodes, ISO series (ISO, 1998), Eurocode (CEN, 2000) and AASHTO (AASHTO, 1998). "International harmonization" and "Performance based design" are important key words. A future task will be to establish the comprehensive design manual having accountability in order to keep up with the development of design code.

SC3 members of TC9 Supporting Committee setup in Japanese Geotechnical Society summarized the current state of Japanese design manuals for reinforced soil wall with considering the developing of design code. In the present paper, the authors introduce the current state and consider some task to establish the comprehensive design manual.

2 CURENT STATE OF JAPANESE DESIGN MANUALS

2.1 *Summarized design manuals*

There are many methods to construct reinforced soil wall in Japan. Geosynthetic Reinforced Soil Wall (GRSW) method, Reinforced Railroad/ Road with Rigid Facing (RRR) method, Terre Armee method, and Multi-Anchored Reinforced Wall (MARW) method are typical of reinforced soil wall methods. Each method has well-examined design manual and design associated tools such as computer program. In this chapter, outline of the manuals of four methods are shown and its contents are compared.

2.2 *GRSW manual*

Public Works Research Institute (PWRI) organized the joint research project on geosynthetics reinforced structures with 20 private companies in the period from 1985 to 1991. As a result of the project, the design manual for geotextile reinforced soil structures was established in 1992 by Public Work Research Center (PWRC). Applications of the manual are for embankments, walls and foundations. Number of geosynthetics reinforced walls constructed with geogrids till 2000 is more than 4000. The manual now in use is the second edition (PWRC, 2000).

Schematic view of GRSW is shown in Fig.1. GRSW is mainly consists of backfill soils, geosynthetics and facings. According to application of GRSW, an optimum facing can be selected from sandbag type, steel wire frame type, PC panel type and PC concrete block type etc. Applicable backfill soil is not only sandy soils but also low compression cohesive soils.

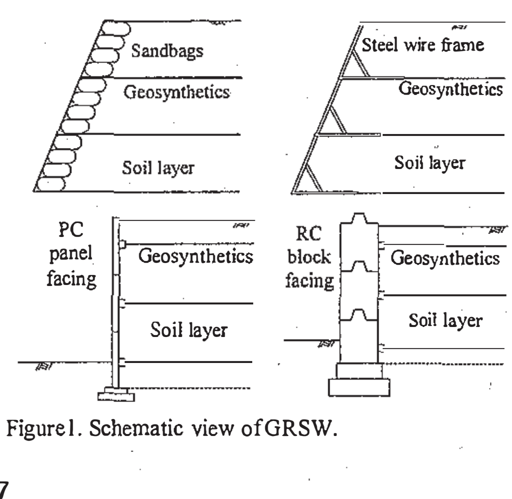

Figure1. Schematic view of GRSW.

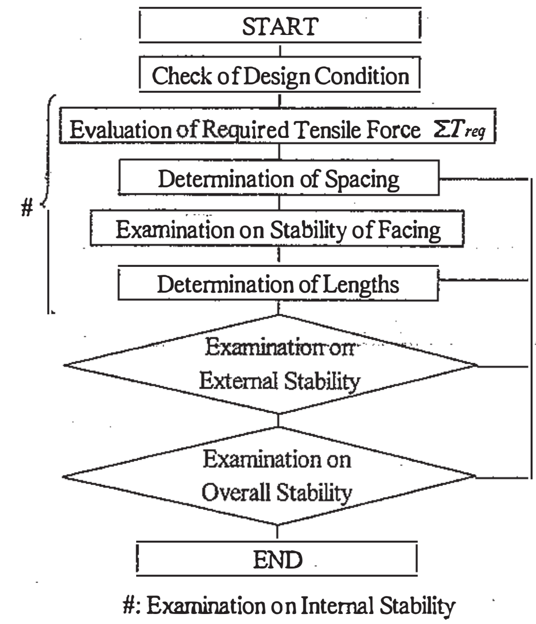

Figure2. Design procedure of GRSW manual.

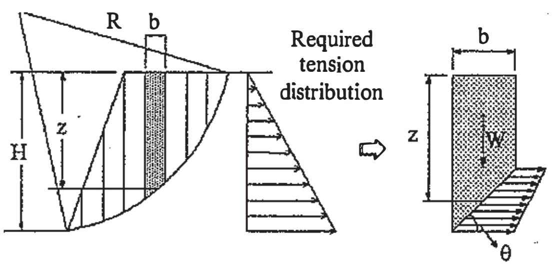

Figure3. Assumption on required tension distribution.

Design procedure is shown in Fig.2. At first, required tensile force ΣT_{req} is calculated by the trial slip method with assuming circular slip line. ΣT_{req} is shown as following equation.

$$\sum T_{req} = \frac{F_s \sum W_i \sin\theta_i - \sum(cl_i + W_i \cos\theta_i \tan\phi)}{\sum \frac{2}{H^2} z_i b \tan\theta_i (\cos\theta_i + \sin\theta_i \tan\phi)} \tag{1}$$

in which, c and $\tan\phi$ are shear strength parameters of soils, the other symbol is shown in Fig.3.

Then spacing and length of geosynthetics are determined with considering tensile strength and pullout resistance of geosynthetics. In this step, triangular distribution of tensile force is assumed as show in Fig.3. Next, stability of facing is examined by conducting equilibrium analysis. Suitable model can be used according to type of facing. After that external stability such as sliding, overturning, bearing capacity of foundation is examined by assuming reinforced zone as a pseudo rigid body. On the bearing capacity, higher value of safety factor is required. Finally, overall stability is checked by the circular slip method. As a design associated tool, a computer soft is prepared.

2.3 *RRR manual*

Railway Technical Research Institute (RTRI) invented reinforced Railroad/ Road with Rigid Facing (RRR) method in 1988. Its application is railroad or road construction. Total distance of RRR walls constructed till 2001 is more than 5000km. The design and construction manual for RRR was published in 1994 by the association of RRR construction system consisted of 49 private companies. The manual now in use is the second edition published by RTRI (RTRI, 2001).

Schematic view of RRR wall is shown in Fig.4. RRR wall is mainly consists of backfill soils, geosynthetics, sandbags and rigid facings. The facing is cast-in-place after full height wall is constructed with wrapped around wall system. Owing to this construction method, damage due to relative settlement between the facing and geosynthetics can be avoided. RRR wall stabilizes with rigid facing function and friction between soils and geosynthetics. By using a proper type of geosynthetics, cohesive soil can also be used as backfill soil.

Design procedure is shown in Fig.5. At first, layout of geosynthetics is assumed. Then failure of reinforced soil (through the toe or slope) due to rupture and pullout of geosynthetics is examined by conducting two-wedge method classified into the trial slip method. Equilibrium condition assumed is shown in Fig.6. In this step, summation of tensile force of geosynthetics, which is more than weight of reinforced zone, is ignored. Next, facing stress analysis is conducted to ensure that it has an adequate stability to resist earth pressure. In this step, rigid facing and geosynthetics are modeled as shown in Fig.7. In the application of RRR method for abutment, it is important to conduct stress analysis for facing with considering spring constant of elastic spring. Finally, overall stability and settlement of subgrade are checked.

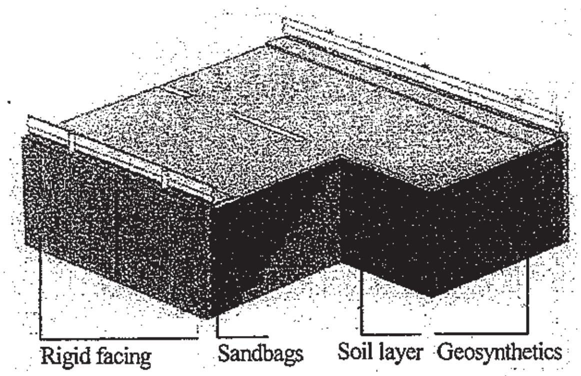

Figure 4. Schematic view of RRR wall.

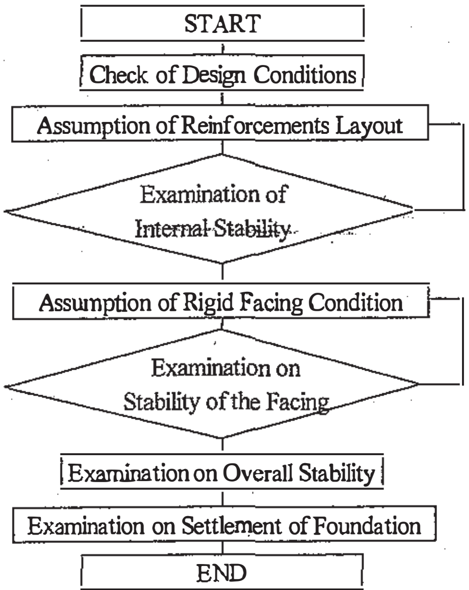

Figure5. Design procedure of RRR manual.

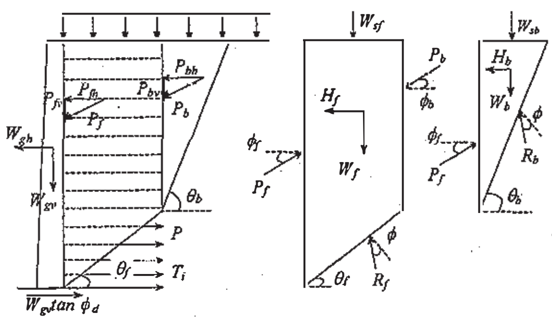

Figure 6. Assumed equilibrium condition.

The RRR manual is mainly applied for soil structure which minimum deformation is requested. In order to ensure the above request, strict requirements are established for reinforcements layout such as vertical spacing of reinforcement h=0.3m. As a design associated tool, a computer soft "Design-RRR for Windows" is prepared.

2.4 *Terre Armee manual*

H.Vidal invented Terre Armee wall method in 1963. The method was introduced for Japan in 1972. After that the method has been improved with considering Japanese traditional retaining wall technique. In Japan, major application of Terre Armee method is road construction and land development. Number of Terre Armee walls constructed till 1995 is more than 8000. The manual for Terre Armee wall was published in 1982 by PWRC. The manual now in use is the second edition (PWRC, 1990).

Schematic view of Terre Armee wall is shown in Fig.8. Terre Armee wall is mainly consists of backfill soils, metallic strips and pre-cast concrete skin or pre-cast metallic skin. Metallic skin is selected in construction of temporary structure. Terre Armee wall stabilizes with friction between soils and metallic strip. Applicable backfill soil is only the sandy soil. In the case that the fine fraction content of backfill soils is over 25% or that maximum grain size is over 300mm, it is requested to cover metallic strip with high quality sandy soil. Standards for metallic strip are established as shown in Table 1. It is feared that metallic strip is corrode due to electric and chemical condition of backfill soil. The manual recommends using of metallic strips planted with zinc. Additionally, standards are established.

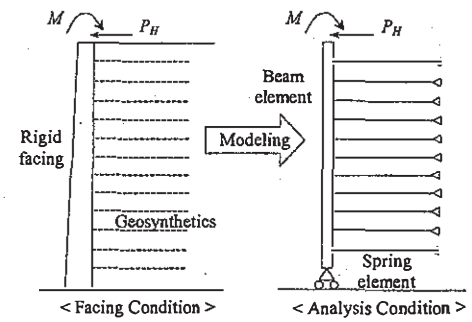

Figure 7. Stress analysis for facing.

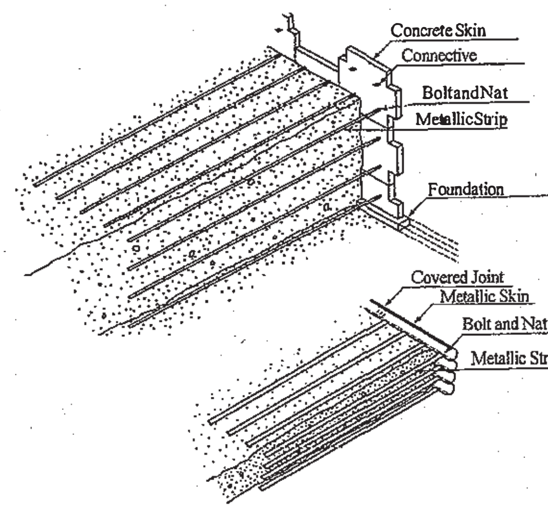

Figure 8. Schematic view of Terre Armee wall

Table1. Standards for reinforcements

	Metal	Dimension	Bolt
Strip with rib	JIS G 3101 SS400	60×5	M16
Strip with high strength rib	JIS G 3106 SM490A	60×4	M12
Flat strip planted with zinc	JIS G 3302 SGH400	100×3.2	M14 M20
Flat strip	JIS G 3101 SS400	100× 2.2~9.0	M14 M20 M22

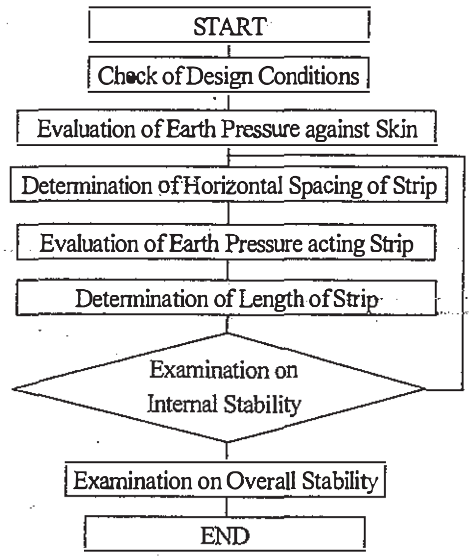

Fig.9 Design procedure of Terre Armee manual

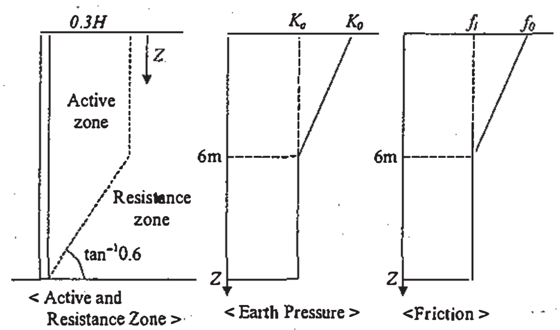

Fig.10 Schematic illustration of internal stability analysis

Design procedure is shown in Fig.9. First, earth pressure acting reinforcement is evaluated by assuming vertical spacing. In this step, the fixed slip line method with assuming bi-linear slip line is used. Schematic illustration to calculate earth pressure is shown in Fig.10. Friction between skin and backfill soils is ignored. Then horizontal spacing and length of reinforcement are determined by considering pullout resistance of metallic strip and allowable stress of the metallic strip. Finally, overall stability and settlement of foundation are checked. In Terre Armee manual, examination on sliding or overturning of reinforced zone is not considered because strict requirements are established for length of reinforcement. Different points between Japanese manual and BS 8006 or NF P 94-220 are as followings. 1)Tensile force of reinforcement at connecting point of skin is 75% of maximum tensile force of reinforcement. 2)Vertical earth pressure acting on reinforced zone is not considered as vertical stress acting on reinforcement. As a design associated tool, some computer soft is prepared. Third edition of the manual will be published soon and some contents will be revised in March 2002.

2.5 *MARW manual*

PWRI invented Multi Anchored Reinforced Wall (MARW) method in 1973. In Japan, major application of MARW is road construction. Constructed quantity of MARW till 2000 is more than 640,000m^2. The design and construction manual for MARW was published in 1994 by PWRC. The manual now in use is the second edition published (PWRC, 1998).

Schematic view of MARW is shown in Fig.11. MARW is mainly consists of backfill soils, tie bar with anchor plates and pre-cast concrete facings. MARW stabilizes with pullout resistance of the anchor plate. Applicable backfill soil is not only sandy soils but also cohesive soils. It is a strong point of this method to able to use cohesive soils such as volcanic cohesive soil (w_L<50%). Standards for facing and reinforcements are established as shown in Table 2. For steel materials used in constructing permanent structure, 1mm margin is anticipated in the cross section and the surface is planted with zinc because corrosion of steel materials is feared.

Design procedure is shown in Fig.12. First, earth pressure against facing is evaluated by fixed slip line method with assuming linear slip line as shown in Fig.13. In this step, friction between facings and backfill soils is considered. Next, requested tensile force is evaluated by considering earth pressure against facing, vertical or horizontal spacing of tie bars and friction between facings and backfill soils. Then a reinforcing material is selected by evaluating pullout resistance of anchor plate and allowable stress of reinforcement.

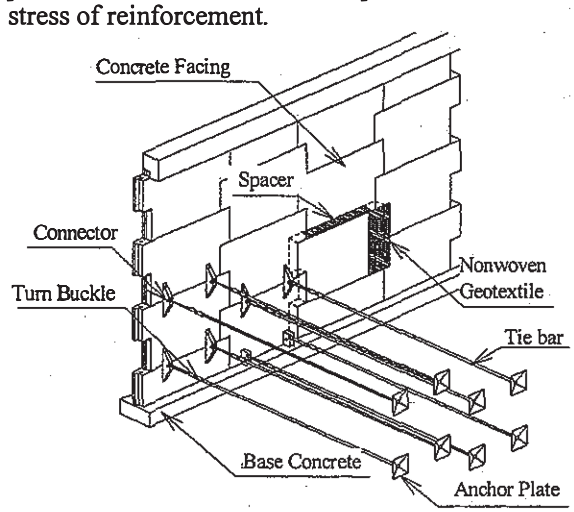

Fig.11 Schematic view of MARW

Table.2 Standards for wall and reinforcements

Element	Standard
Concrete Facing	JIS A 5308
Anchor Plate	JIS G 3101
Tie Bar	JIS G 3101
Turn Buckle	JIS G 3445

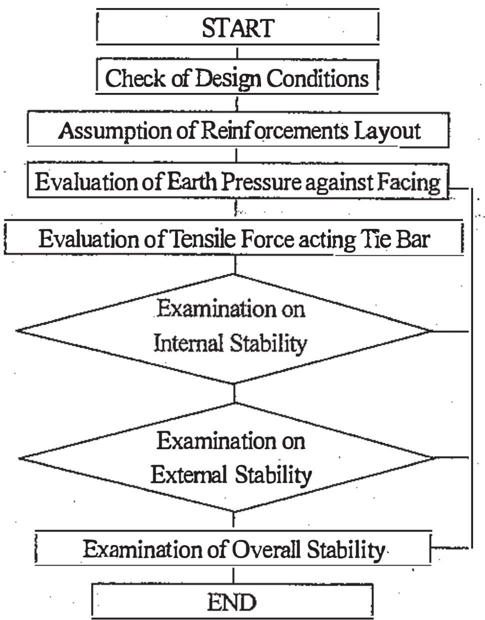

Fig.12 Design procedure of MARW manual

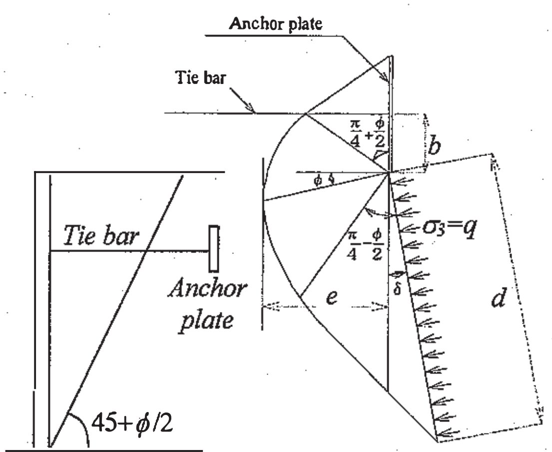

Fig.13 Schematic of internal stability analysis

The pullout resistance of an anchor plate is calculated by using following equation based on the concept shown in Fig.13.

$$P = cN_c + qN_q \tag{2}$$

in which N_c and N_q are pullout resistance factor calculated by numerical analysis solving kotter's equation in axis-symmetric condition. q is confining stress. The factors to typical condition are given as numeric table in the manual.

In the external stability analysis, length of tie bar is determined by conducting the external stability analysis. In the external stability analysis, sliding of reinforced zone and bearing capacity of foundation are examined. Finally, overall stability is checked by the slip circular method. As a design associated tool, a computer soft is prepared.

3 COMPARISON OF DESIGH MANUALS

3.1 *Basic concept on the comparison*

In order to keep up with development of design code such as ISO, Eurocode and AASHTO, it is needed to establish the comprehensive design manual. The authors compared four Japanese design manuals shown in the former chapter on following items.

1) Components.
2) Requirements for limit states.
3) Requirements for serviceability.
4) Actions.
5) Design values for components.
6) Restriction for layout of reinforcements.

Objection of this comparison is to search common concept or better way to harmonization but not to value the best manual. Results of the comparison are summarized in Table 3. In this chapter, each compared item is considered. Such research will contribute the harmonization of various manuals.

3.2 *Requirements for limit states*

In all manuals, rupture and pullout of reinforcements are examined by conducting the internal stability analysis however determination of reinforcements layout is different from each other. In GRSW manual, Terre Armee manual and MARW manual, the layout is determined by considering required tensile force calculated by limit equilibrium analysis. In RRR manual, the layout is determined by conducting assumption of layout and the internal stability analysis in turn. As a method to calculate the required tensile force, there are the trial slip method and the fixed line method. The former method is carried out in the case of using flexible and planer reinforcements such as geosynthetics. The latter method is carried out in the case of using rigid and strip type reinforcements such as metallic strips.

External stability of reinforced soil wall is considered in all manuals. In Terre Armee the manual, stability analysis on sliding or overturning of reinforced zone is not requested. But strict requirement is established for length of reinforcements so that sliding or overturning of reinforced zone does not occurred. In RRR manual, the external stability is examined in an evaluating step for internal stability.

In all manuals, it is recommended to examine overall stability by conducting the circular slip method. In Japan, most of constructed site has soft alluvial soil. Effectiveness of the circular slip method is cleared to evaluate stability of the embankment on soft ground. That is seemed to be a reason.

Various safety factors are considered in stability analysis of reinforced soil wall. Allowable safety factor is different from each manual. It is different to prove theoretically what each safety factor means.

Table 3. Comparison of four design manuals for reinforced soil wall in Japan

				GRSW manual	RRR manual	Terre Armee manual	MARW manual
Components	Facings			Flexible facing system or Rigid facing system	Wrapped around system + post cast concrete facing	Concrete or metal panel	
	Reinforcements			Geogrid, non-woven geotextile		Metallic strip	Tie-bar with anchor palate
	Backfill soils	Reconunend		Grained soil		$25<F_c$[3], $d_{max}<300$mm	Grained soil
		Acceptable		Gravel		$25<F_c<35$, $75\text{mm}<d_{max}$	Gravel
		Possible		Fine-grained soil		—	Fine-grained soil
		Impossible		Organic soil		—	Organic soil
Requirements for Limit States	Internal stability	Considered failure modes		Collapses of reinforced zone with breaking or pulling out of reinforcements			
		Analysis method		Trial slip line method		Fixed slip line method	
		Assumed failure patterns		Circular	Bi-linear	Bi-linear	Linear
		Allowable SF[1]		1.2	2.0	—	
	External or Overall stability	Allowable SF	Overall sliding	1.2	1.4	1.2	
			Bearing Capacity	2.0	3.0	—	3.0
			Sliding	1.5	Checked by Internal stability analysis		1.5
			Overturning	$e \leq L/6$			—
	Facing stability	Considered failure modes		Depends on facing type	Bending or shear failure of panel		
		Allowable SF			1.0 (working stress < allowable stress)		
Requirements for Serviceability	Facing deformation			In rigid facing system (concrete facing), requirements of Terre Armee manual are applied.	—	$\pm 0.03H$ or ± 30cm (H: wall height)	
	Foundation deformation	Residual settlement (cm)			10	30	—
		Differential settlement (%)			—	Concrete panel: 3% Metal panel: 1.5%	3%
Actions	Permanent	Overburden pressure		Uniform distribution load (width of load is finite or infinite)			
		Ground water pressure		Considered as pore pressure in effective stress analysis			
	Accident	Earthquake loads		In the static lateral force method, design horizontal seismic coefficient is determined according to zone and soil conditions			
Design Values for Components	Soils	Shear strength	Parameters	c, $\tan\phi$	$\tan\phi$		c, $\tan\phi$
			MSF[2]	1.0			
	Reinforce-ments	Tensile strength	MSF	1.7～2.0[4]	1.25～2.0[5]	1.7	
		Pullout strength	Evaluation	$P = 2L_r(c^* + \sigma \tan\phi^*)$[6]		$P = 2bL_r\sigma\tan\phi^*$[7]	$P = cN_c + qN_q$[8]
			MSF	2.0			3.0
	Facings	Bending or shear strength		Determined based on the concept of limit state design or reliability theorem			
Restriction for Layout of Reinforcements		Vertical spacing h (m)		$h \leq 1.2$	$h = 0.3$	$0.375 \leq h \leq 0.75$	$0.5 \leq h \leq 1.0$
		Length L (m)		$1.0 \leq L_e$[9]	1.5 or $0.35H \leq L$	Bottom layer $0.4H \leq L$ Top layer $0.7H \leq L$	$4.5 \leq L$
Associated Tools for Design				Computer program, Design chart and Numeric table for design			

1)SF: Safety factor, 2)MSF: Material safety factor, 3)F_c: fine fraction content, 4)determined by creep, durability and damage test etc. 5) depends on kind of load such as general, temporary and earthquake load. 6)L_r: bonded length of reinforcement, c^* or $\tan\phi^*$: cohesion or friction angle between reinforcement and soil, 7)b: width of reinforcement, 8)N_c or N_q: pullout resistance factor, 9)L_e: length of reinforcement in active zone

However it seems that the present safety factor has reasonability to same extent. In ISO 2394, statistical (reliability) analysis is recommended to evaluate the stability of structure. It is important to clear the engineering value of the present safety factor by conducting reliability analysis to various conditions. Such examination will contribute to the establishment of limit state design or performance based design.

3.3 *Requirements for serviceability*

Deformation of facing and foundation is considered as requirements for serviceability of reinforced soil wall. On the facing deformation, a specific allowable value is established in the only Terre Armee manual. In RRR manual which minimum deformation is required, a specific allowable value is not established however strict requirement are established for reinforcement layout such as vertical spacing h=0.3m. On the foundation deformation, it is recommended to examine consolidation settlement and differential settlement in the most of manual. In RRR method, post-cast concrete facing is constructed after dissipating of settlement. Therefore it is important to predict the end of consolidation. Observational method is effective for the settlement prediction.

Recently, FE analysis is often conducted in the practical geotechnical engineering fields. The FE analysis is effective to examine the serviceability of reinforced soil structures but not enough established (Yashima, 1996). It is difficult to evaluate not only interaction property between soil and reinforcements but also constitutive relation of compacted saturated soils. It is necessary to investigate numerical model of soils, reinforcements and interaction. Additionally, it is also important to store field data and model test results in order to examine solutions for various serviceability limits.

3.4 *Actions*

Both of traffic load and seismic action are considered as actions for reinforced soil wall in all manuals. Distribution of live load caused the traffic is assumed in common as shown in Fig.14 however there are slight differences in detailed assumption such as impact area, distributing effect of the load.

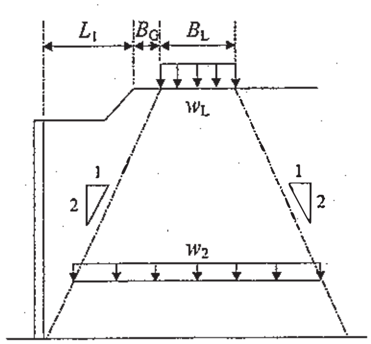

Fig.14 Assumed distribution of live load caused the traffic

Evaluation of the seismic action is more important in design of permanent structure. In Japan, the static lateral force method is used in the most of seismic geotechnical design. In this analysis, design horizontal seismic coefficient is determined by using following equation.

$$k_h = c_1 c_2 k_{h0} \tag{3}$$

in which, k_h is design horizontal seismic coefficient, k_{h0} is standard design seismic coefficient, c_1 is modification coefficient depending on constructed region and c_2 is modification coefficient depending on ground condition.

Actions, which affect limit state or serviceability of reinforced soil wall, is not only traffic load and seismic action but also other actions such as changing of ground water table in the backfill soil, snow, temperature and so on. It is important to evaluate the combined load with considering frequency of the actions.

3.5 *Design values for components*

Design values on soil strength are determined by conducting laboratory test or by referencing standard values shown in each manual or by estimating with other geo-information. In all manuals material safety factor of soils is not shown however some advice are shown. Design values on soil strength depend on engineer's judgments.

Determination of design value on tensile strength of reinforcement depends on whether reinforcement is geosynthetics or metals (Hayashi et al, 1996). Design value of metal is based on the allowable stress concept. The other side, design value of geosynthetics is determined by following equation in GRSW manual.

$$T_A = \frac{T_{max}}{F_{cr} \cdot F_D \cdot F_C \cdot F_B} \tag{4}$$

in which, T_{max} is maximum tensile strength, F_{cr} is safety factor(S_f) for creep, F_D is S_f for durability, F_C is S_f for damage during construction work and F_B is S_f for reduction of strength at joints.

In the manual, total material safety factor on tensile strength change from 1.7 to 2.0 according to king of products. In RRR manual, following equation is used.

$$\begin{aligned} &\text{For general load: } T_{AG} = \alpha_1 \alpha_2 \alpha_3 T_{max} \\ &\text{For temporary load: } T_{AG} = \alpha_1 \alpha_2 \alpha_5 T_{max} \\ &\text{For earthquake load: } T_{AG} = \alpha_1 \alpha_2 \alpha_4 T_{max} \end{aligned} \tag{5}$$

in which, T_A is design tensile strength, T_{max} is maximum tensile strength, α_1 is alkali degradation coefficient, α_2 is construction time reduction coefficient,

α_3 is creep reduction coefficient, α_4 is momentary load reduction coefficient, α_5 is train load reduction coefficient.

Safety factor on pullout resistance of reinforcement is 2.0 for the friction resistance or 2.0–3.0 for the bearing resistance. Pullout resistance mobilized in the backfill soil depends on soil condition such as density or water content, material property of reinforcement and stress condition etc. Therefore, it seems that relatively higher value is established as safety factor.

Design values on concrete facing are based on the concept of limit state design or reliability theorem. Characteristic value of concrete is determined by following equations (JIS A 5308).

$$f'_{ck} = f'_{cm}(1 - 1.73\sigma_c) \quad (6)$$

in which f'_{ck} is a design value, f'_{cm} is a average strength and σ_c is standard variation of strength. Design value is evaluated by dividing the characteristic value by material factor.

Reinforced soil wall consist of backfill soils, reinforcements and facing materials. At present, concept to evaluate design values is different for each component. Same concept should be introduced for all design value in design of reinforced soil wall. Viewing the present developing of design code, the limit state design concept will be suitable as concept to evaluate design values.

4 SUMMARIES

In first half of the present paper, outlines of Japanese design manuals are shown. Above-mentioned methods are Geosynthetic Reinforced Soil Wall (GRSW) method, Reinforced Railroad/ Road with Rigid Facing (RRR) method, Terre Armee method, and Multi-Anchored Reinforced Wall (MARW) method. In the latter, contents of design manual are compared and some task to establish the comprehensive design manual is considered. Summaries of the comparisons and the considerations are as follows.

(1) Various safety factors are used in each manual. It is important to clear engineering values of the safety factors in order to establish the comprehensive design manual. In this case, reliability analysis is a good analytical tool.
(2) In the manuals, deformation of facing and foundation is considered as requirements for serviceability of reinforced soil wall. FE analysis is effective for the consideration. It is necessary to investigate numerical model and to store field data and model test results in order to examine solutions for various serviceability limits.
(3) Both of traffic load and seismic action are considered as actions for reinforced soil wall in all manuals. Other many actions should be considered in the design. It is important to evaluate the combined load with considering frequency of the actions.
(4) Some concept is used to evaluate design values of backfill soils, reinforcements and facing in the present manuals. Viewing the developing of design code, the limit state design concept will be suitable as concept to evaluate design value.

It is important to chain each design process such as establishment of requested performance, determination of design values, structural analysis and evaluation of environmental impact with LCA. Academic researchers and practical engineers who concern the reinforced soil technique are necessary to establish the comprehensive design manual having accountability.

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