Inspection of structural health of existing railway retaining walls

Inspection de l'état structurel des murs de soutènement des voies de chemin de fer existantes

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ABSTRACT: This study aims to develop an inspection method of a structural health of the existing retaining walls. This paper begins with the brief introduction of the current state of the existing retaining structures. Second, applicability of the percussion test for the evaluation of structural health of existing retaining wall is examined by conducting a large numbers of the percussion test on retaining walls at the site. It was found from the percussion test that structural health of the ashlars wall could be quantitatively evaluated by the percussion test while it was found to be difficult to apply the percussion test for the quantitative evaluation of the leaning type retaining wall. Third, applicability of the small scale vibrator, which was newly developed to improve the disadvantage of the percussion test as the inspection method of the retaining wall, was examined thorough the prototype scale model test on the existing leaning type retaining wall. It was found from the series of model test that the vibration tests were effective in evaluating the characteristics of dynamic properties of the retaining walls, which were affected by structural health of the retaining walls. This result indicated that the small scale vibration tests could be applicable to evaluate the structural health of the existing retaining structures.

RÉSUMÉ : Cette étude vise au développement d'une méthode d'inspection de l'état structurel des murs de soutènement existants. L'article commence par une brève présentation de l'état actuel des structures de soutènement existantes. Il se poursuit par l'exposition de l'analyse de l'applicabilité des essais aux chocs à l'évaluation de l'état structurel des murs de soutènement existants conduits sur des murs de soutènement sur le terrain. Ces essais aux chocs ont montré qu'ils permettaient une évaluation quantitative des murs de soutènement de type en béton mais qu'ils ne se prêtaient guère à l'évaluation des murs de soutènement de type incliné. Une troisième partie est consacrée à l'applicabilité d'un vibrateur à faible échelle nouvellement mis au point qui permet de palier les inconvénients des essais aux chocs comme méthode d'inspection des murs de soutènement. Un appareil prototype a été utilisé pour l'inspection des murs de soutènement de type incliné. La série d'essais modèles conduite a mis en évidence que les essais aux vibrations permettaient de bien évaluer les caractéristiques des propriétés dynamiques des murs de soutènement affectés par leur état structurel. Les auteurs concluent que les essais aux vibrations à petite échelle peuvent être appliqués dans l'évaluation de l'état structurel des murs de soutènement existants.

KEYWORDS: Retaining walls, condition rating, small scale exciter, vibration testing

1 BACKGROUND

In Japan, there are many old existing railway structures and it enhances the importance of the proper maintenance methodology. For the proper management of the railway structures, it is important to detect deformations of the structures in early stage. Once deformations are observed, continuous observations and retrofitting works are also important. As for the Japanese railway structures, it has already developed to evaluate a structural health of bridge piers quantitatively, which makes it possible to maintain structures efficiently. On the other hand, a visual inspection is still conducted to evaluate a structural health of the existing retaining walls because quantitative inspection method for the existing retaining wall has not yet developed. It is required to evaluate a structural health of the existing retaining walls quantitatively because a result of the visual inspection is highly dependent on the subjective judgment of an inspector.

Based on the background above, this study aims to develop an inspection method for the condition rating of the existing retaining walls.

2 CURRENT STATE OF THE RAILWAY RETAINING STRUCTURE

2.1 *Maintenance standards in Japan*

There are approximately 30 thousand kilometers of the railway lines in Japan, which are operated by many railway organizations (seven Japan Railway companies, over 100 private railway companies and several local governments). Japanese railway organi-zations maintain their structures safety conditions by referring to the Japanese maintenance code of Maintenance Standards in Japan (RTRI, 2007). General procedure for structural maintenance in the Management standards and relationships between the soundness and the structure state are shown in Figure 1 and Table 1.

As indicated in Figure 1, "General Inspection" is conducted to all of the railway structures within the intervals of two years mainly by visual inspection. On the other hand, "Individual

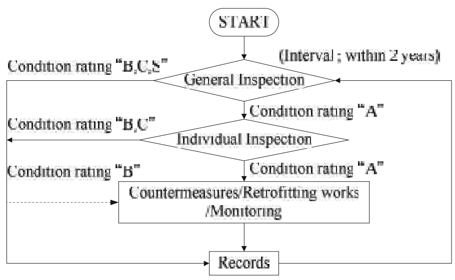


Figure 1. Maintenance procedure according to the Maintenance standards in Japan

Table 1. Relationships between rated condition and structure state

Condition rating	Structure state
A	State that threatens operational safety, safety of passengers, public safety, gurantee of regular train operation, or deterioration that might cause this state
B	Deterioration that might result in a future soundness rank of A
C	Slight deterioration
S	Good condition

Inspection" is performed to the specific structures in which severe deterioration are detected at the time of the General Inspection by means of detailed visual survey or using measuring equipments. As discussed in BACKGROUND, this study aims to develop a methodology which can be used for the condition rating of the retaining walls quantitatively as an alternative method of detailed visual survey.

2.2 *Survey on current state of Japanese railway retaining walls*

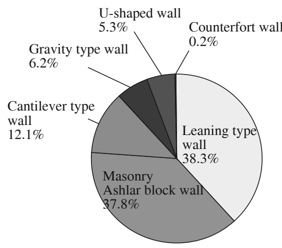
A preliminary survey on current state of Japanese railway retaining structures was conducted. In the preliminary survey, information of typical types of retaining walls in Japan was extracted from the database of the "Structural Management Supporting system (SMS)" (Oyado et al. 2010). In total, the data of 7,989 sites could be extracted. Figure 2 shows the relationships between the type of retaining wall and construction length, which could be obtained using the efficient 1,657 sites data. Construction length of the leaning type retaining wall stands first among all the types of the retaining walls and it accounted for 38.3 % of the efficient data. The percentage of the masonry and ashlar block retaining wall reaches to 37.8 % as well. It was found from the above survey that the leaning type and masonry or ashlar block retaining wall occupies 76.1 % of the total construction length and it indicated the importance of the management of these structures.

2.3 *Deformation of retaining walls*

Deformation of the railway retaining structures can be divided into two groups; one is the deformation due to destabilization, the other one is the deformation due to deterioration. Typical deformation of the railway retaining structures is schematically illustrated in Figure 3.

Settlement, inclination, swelling, difference in level and difference at construction joint due to external thrusts can be categorized to the deformation due to the destabilization. Exfoliation of concrete, clogging of the drainage facilities is categorized to the deformation due to the deterioration. Cyclic load due to the train passing, increase of earth pressure due to the additional construction of the embankment, increase of dynamic earth pressure due to the earthquake, increase of water pressure due to the change of the water level in backfill soil are thought to be the source of the external thrusts, which could cause the deformation due to the destabilization.

On the other hand, deterioration is thought to be caused by the cyclic change of the thermal or humid condition during the long period of its use. Deformation due to the destabilization could be secondary source of the deformation like backfill loosening, bearing capacity failure. Therefore, early detection and retrofitting work against the deformation due to the destabilization are highly important, while it has not yet been developed a methodology to detect such phenomenon by the nondestructive tests. Based on the discussion above, development of a nondestructive evaluation method of the existing retaining wall is attempted in this study.



Type of wall	Number	Length(km)
Leaning type	409	41.1
Masonry/Ashlar block	802	40.6
Cantilevet type wall	249	13.0
Gravity type wall	85	6.7
U-shaped wall	105	5.7
Counterfort wall	7	0.2
Total	1,657	107.3

Figure 2. Relationships between construction length and types of retaining wall

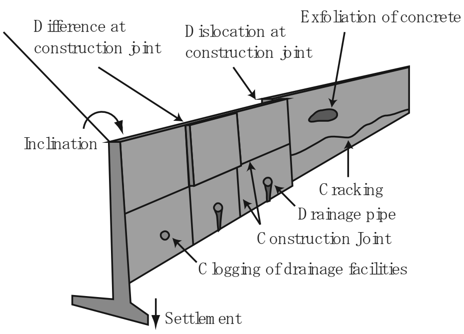


Figure 3. Typical deformation of retaining wall

3 APPLICATION OF PERCUSSION TEST FOR CONDITION RATING OF RETAINING STRUCTURES

3.1 *Percussion test*

In Japanese railway field works, nondestructive evaluation of the bridge substructure has been carried out by conducting a percussion test (Nishimura et al. 1989) . In the percussion test, the natural frequency of the bridge pier is measured with high accuracy and it is used for the evaluation of the structural health of the pier. This method was based on the knowledge that the natural frequency of the bridge substructure decreased with the damage of the structures and increased with the reinforcement.

Natural frequency of the bridge piers is evaluated by carrying out a spectrum analysis using measured free vibration, which is recorded by velocity sensors. Free vibration is induced by hitting the top of the piers using an iron ball. In practice, current performance of bridge pier can be evaluated by comparing the measured natural frequency with the one of immediately after the construction or the criterion of the potential natural frequency. Potential natural frequency is the experimentally-based proposed value by Railway Technical Research Institute so as to be used for the site where the natural frequency immediately after the construction was not recorded.

3.2 *Site test results*

A series of site test was carried out so as to examine the applicability of percussion test for the condition rating of retaining wall. In the series of site tests, leaning type and ashlars wall are highlighed because construction length of these types of retaining wall was much longer than the other types of walls. As summraized in Table 2, 52 site tests were carried out by selecting the deformed and sound retaining walls so as to investigate into the difference of the vibration characterestics of retaining wall. Percussion test was conducted by hitting the iron ball at the top of the retainig wall and vibration was measured by the velocity sencers attached at the top, middle and bottom of the retaining wall.

Figure 4 shows an example of test result obtained from test No. 3. Predominant frequency of 26.6 Hz could be evaluated based on the changes of phase angle, while the peak amplitude was not clearly observed. This behavior indicates that natural frequency based condition rating, which has been adopted in the condition rating of the bridge substructure, was difficult possibly because the mode of vibration of retaining walls are generally more complicated than the oridinally bridge substructures. As an alternative index for the condition rating of the retaining wall, the authors proposed the value of spectrum area Sa, which could be evaluated by integrating the Fourier's spectrum of the amplitude as schmatically illustrated in Figure 4b), while frequency range of 3 to 40 Hz was selected in this study. Figures 5 and 6 show the relationships between results of condition rating based on visual inspection and the values of

Table 2 Summary of test sites in this study

No.	Company	Type	Height(m)	Deformation
1	A	Leaning	7.2	None
2			7.2	None
3			7.2	Cracking
4			7.2	None
5			7.2	None
6			7.2	None
7			7.2	None
8	B	Leaning	6.3	Cracking
9			6.3	Cracking Horizontal disp.
10			6.3	Cracking
11			6.3	None
12			3.9	Cracking
13			3.35	None
14	C	Leaning	3.6	None
15			3.6	None
16			3.6	None
17			3.6	None
18	D	Gravity	4..8	None
19			4.3	None
20			3.3	None
21			3.7	Cracking
22			2.9	Cracking
23			3.2	None
24	E	Leaning	4.15	None
25			4.15	None
26	F	Leaning	3	None
27			2.64	None
28	G	Leaning	3.95	None
29	H	Leaning	5.48	Cracking
30			5.48	Cracking
31			5.48	Cracking
32	I	Ashlars wall	5.4	Cracking
33			6.4	None
34			2.4	Cracking
35	J	Ashlars wall	4.2	None
36			4.1	None
37			4.1	None
38			4.1	None
39	K	Ashlars wall	4	Inclination
40			4	Inclination
41			4	Inclination
42			4	Inclination
43	L	Ashlars wall	5.7	Cracking
44			5.4	None
45	M	Ashlars wall	2.6	None
46			3	None
47			3.4	None
48	N	Ashlars wall	3.3	None
49			3.3	None
50			3.3	None
51			3.3	None
52			3.3	None

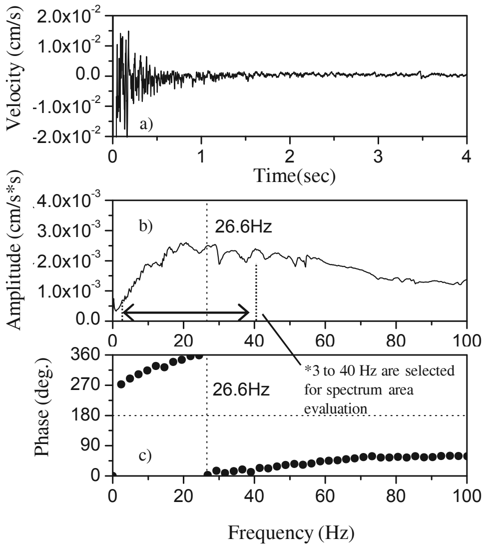


Figure 4. Example of test result obtained from site No.3

spectrum area. In the cases of ashlars wall shown in Figure 5, the values of spectrum area Sa of retainig walls rated as "A(deformed)" were genellary larger than the ones of retainig walls rated as "B(no deformation)", which shows the validity of spectrum area for the condition rating of retaining walls.

In the cases of the leaning type retainig wall shown in Figure 6, a good corelation between the result of visually inspected condition rating and the values of spectrum area could not be found. In the sites No. 6, 20, 21 and 24, the values of spectrum area was much larger than the other sites although they were rated as "B (no deformation)", which might imply that the progress of the deformation at the part in which is difficult to detect by visual inspection (e.g. subsoi, backfill, etc.). On the other hand, at the sites 27, 26, 25 and 3, the values of spectrum area were not necessarily larger than the other sites although they were categorized as "A(deformed)".

Percussion test has some problems (Nakajima et al., 2012) ; 1) heavy weight of iron ball (safety, portability) , 2) scattering of impact force depending on inspectors (repeatability) and 3) attenuation of inpact force especially in high frequency range(limited range of input frequency). In applying to the condition rating of retaining wall, second and third problems would make it difficult to rate the condition of the retaining wall properly especially in the case of the leaning type retaining wall. Therefore, the authors developed a small scale exciter (Shinoda et al., 2012), which could apply constant sweep sinusoidal excitation under mechanically manupulation, which could solve second and third problems. A prototype scale loading test on leanining type retaining wall model was conducted so as to examine the applicability of the newly developed small scale exciter.

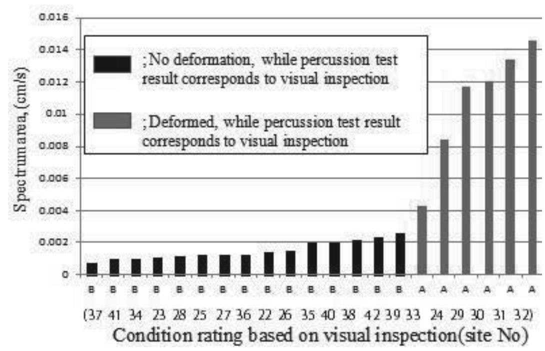


Figure 5. Relationships between condition rating by visual inspection and value of spectrum area (Ashlars wall)

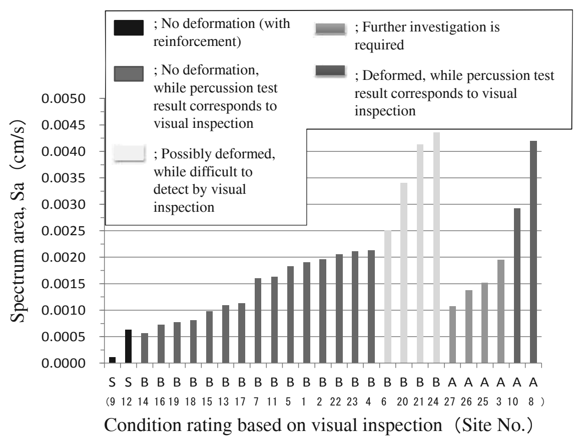
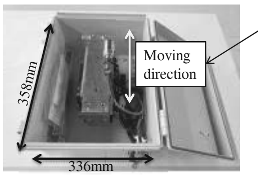


Figure 6. Relationships between condition rating by visual inspection and value of spectrum area (Leaning type retaining wall)

4 PROTOTYPE SCALE LOADING TEST

Cross section of constructed leaning type retaining wall with height of 4.3 m and width of 1.5 m is shown in Figure 7. In Figure 7, the outline of the develope small scale exciter is also summarized. Retaining wall was constructed on the stiff base layer while its backfill consisted of the cobbles, sand backfill with degree of compaction D_c of 90 % and densely compacted gravelly sand. In the loading test, the retaining wall was subjected to the cyclic loading and unloading processes by applying the vertical load at the surface of the backfill using the hydraoulic jack while their amplitude were gradually increased as shown in Figure 8. Gravelly sand layer inclined 30 degrees from the horizontal direction so as to apply horizontal load to the retaining wall efficently.

In the loading test, cyclic loading and unloading proccesses were applied to the leaning type retaining wall model (Case 1). A soil nailing reinforcement with diameter of 60 mm and length of 4000 mm was installed after horizontal displacement at the wall top exceeded 50 mm. As the second case (Case 2), the model wall reinforced with the top nailing was subjected same loading and unloading processes with Case 1. Lastly, the model wall with top and bottom nailing, which was installed after Case 2, was subjected to the same loading processes while the maximum amplitude of load was applied to the wall in the end



Rated sine force (N)	98
Max. displacement (mm)	80
Max. velocity (cm/s)	74.8
Max. acceleration (m/s²)	14
Frequency range (Hz)	3-200
Shipping weight (N)	147

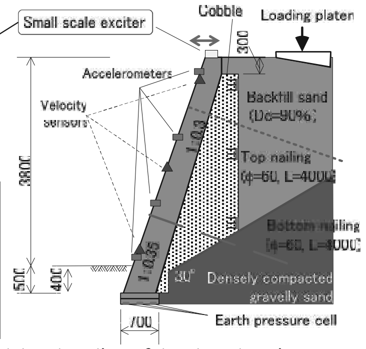


Figure 7. Cross section of model and outline of developed exciter (unit in mm)

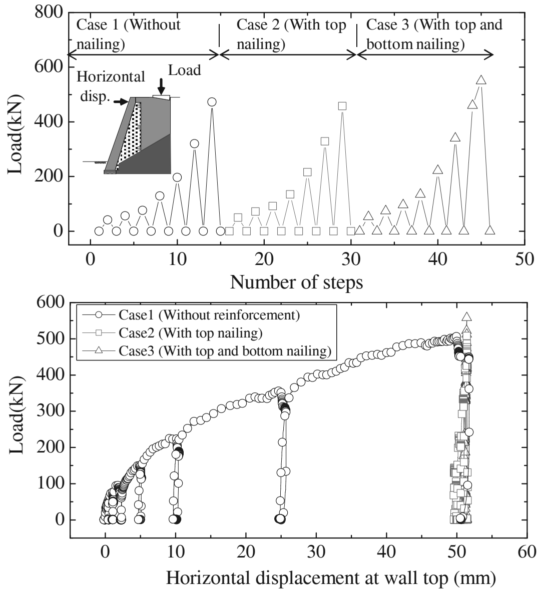


Figure 8. Loading process and load-displacement relationships

of loading process (Case 3). The loading and unloading processes in each case were summarized in Figure 8.

At every loading and unloading process, sets of percussion test with a set of velocity sencers and vibration tests using the developed small scale exciter with a set of accelerometers were conducted so as to investigate into the difference of vibration characterestics obtained from each test. Vibration test was conducted by applying the sinusoidal sweep excitation to the retaining wall model by the small scale exciter fixed at the top of the retaining wall, while the constant amplitude of 1000 gals with frequency range of 3 to 100 Hz and sweeping rate of 3 Hz/sec were adopted as the test condition.

Figure 8 also shows load-displacement relationships obtaied from the loadcell installed at the hydraulic jack and displacement transducer at the top of the retaining wall. As clearly shown in Figure 8, the increment of the wall top displacement was drastically reduced by adding the soil nailing although the same amplitude of loading processes were applied to the wall. Displacement increment during a set of loading and unloading processes in Cases 1, 2 and 3 were 50mm, 1.0mm and 0.5 mm respectively.

Figure 9 shows relationships between the number of step and the results from the percussion test and vibration test, while the values of spectrum area of frequency range of 3 to 40 Hz were plotted in the virtical axes. It should be empasized that the spectrum area evaluated from the pecussion test results Sa[p] has the dimension of velocity (cm/sec) because it was evaluated from the integration of the relationships between the Fourier's amplitude of velocity (cm/sec*sec) computed from records of the velocity sensor at the top of the wall and the freauency

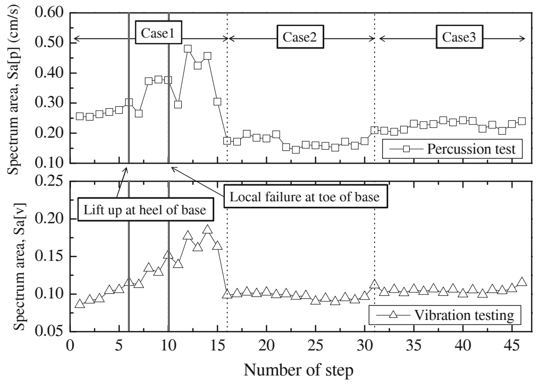


Figure 9. Cross section of model (unit in mm)

(1/sec). On the other hand, the spectrum area calculated from the vibration testing Sa[v] did not have any dimensions because it was evaluated from the transfer function of the top accelerometer against the input acceleration.

It was found from Figure 9 that the values of Sa[p] and Sa[v] increased with the number of step. Moreover, the effect of the nailing could be also detected as the reduction of the values of Sa[p] and Sa[v] in Cases 2 and 3 as compared with Case 1. The diffrence between Sa[p] and Sa[v] could be found especially in loading and unloading process. The values of Sa[v] increased in the loading process and reduced in the unloading process, which indicated that the spectram area Sa[v] based condition rating using the vibration testing with the small scale exciter could detect a minor change of the stability of the retaining wall. The value of Sa[p], however, could not detect a minor change during single loading and unloading process, which was possibly because the input force could not be kept constant. It was found from the results of the site tests and prototype scale loading test that the percussion test and the vibration testing could be applicable, while vibration testing could detect a minor change of the stability of the retaining wall.

5 SUMMARY

It was attempted in this study to develop a inspection method of the existing retaining wall. It was found from the preliminary survey on the current state of Japanese railway retaining wall that condition rating of the leaning and the ashlars wall are important because of their huge amount of existing structures.
Based on the site test and prototype scale loading test, it was found that the percussion test and vibration test using the spectrum as an index could be applicable for the condition rating of existing retaining walls.

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