EFFICIENT SAFTY ASSESSMENT OF EXPRESSWAY SLOPE REINFORCED BY GROUND ANCHORS BASED ON RESIDUAL TENSILE LOAD EVALUATED BY VIBRATION METHOD

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ABSTRACT

Ground Anchoring is one of the popular methods for maintaining the stability of expressway slope. Expressway companies have carried out the mandatory inspections including the confirmation of the residual tensile load of 5% of total anchors or at least 5 anchors for each anchored slope every five years. The residual tensile load of anchor is usually measured by the lift-off test with the center hole jack, which sometimes requires a temporary scaffold and typically requires time and costs. The authors have proposed a new method of non-destructive evaluation for residual tensile load of anchor by the “vibration method” based on the assumption of “string” of anchor tendon tension part. Based on the proposed technique, it is easily possible to obtain the residual tensile load by the frequency of the free vibration of tendon tension part, line density and tendon free length. A series of on-site measurement for various type anchors were conducted by using the proposed technique. It is found out that the proposed technique can easily evaluate the magnitude of the residual tensile load of anchor with the error of about 5%. The maintenance engineers can quantitatively evaluate the safety of anchored slope using the proposed technique.

1. INTRODUCTION

Ground Anchoring is one of the popular methods for maintaining the stability of highway slope. The anchoring method was first applied to expressways in 1969 in Japan and the number increased gradually from around 1985. The present number of anchors constructed along the expressways in Japan is over 120,000 [1], [2]. To maintain the stabilizing function of the anchors, it is necessary that the anchors are not corroded and maintain residual tensile load within the expected range. The soundness of anchor is evaluated based on the Guideline for the evaluation of residual tensile load [3], [4] (see Table 1). Periodic inspections of anchors are important to ensure the slope stability. Expressway companies have carried out the mandatory inspections including the confirmation of the residual tensile load of 5% of total anchors or at least 5 anchors for each anchored slope every five years in accordance with the maintenance manual [5] and survey manual [6].

The residual tensile load of anchor is usually measured by the lift-off test with the center hole jack, which sometimes requires a temporary scaffold and typically requires time and costs (see Photograph 1). Expressway is the essential network. Therefore, it is very difficult to close the road to traffic for on-site inspection work. We should carry out on-site inspection work under the heavy traffic condition with traffic lane regulation. To satisfy this requirement, much more convenient as well as less expensive technique for evaluating the residual tensile load of anchor has been long awaited.

Table 1 Guideline for evaluation of residual tensile load [3], [4]

Range of residual tensile load	Evaluation	Situation
	D	Possibility of failure
0.9 T_{ys}	C	Possibility of dengerous situation
0.65 T_{us}	B	Tendency to drop of soundness
0.6 T_{us}	A	Sound
0.3 T_{us}	B	Tendency to drop of soundness
0.1 T_{us}	C	Non-function
	D	Pull up, jump out is seen

T_{ys} : Tendon yield strength , T_{us} : Tendon ultimate strength

Photograph 1 Center hole jack and scaffold used for lift-off test

In our research project, we have proposed a new method of non-destructive evaluation for residual tensile load of anchor by the “vibration method” based on the assumption of “string” of anchor tendon tension part. Based on the proposed technique, it is easily possible to obtain the residual tensile load by the frequency of the free vibration of tendon tension part, line density and tendon free length.

A series of full-scale model experiments and on-site measurements for various type anchors were conducted by using the proposed technique. It is found out that the proposed technique can easily evaluate the magnitude of the residual tensile load of anchor with the error of about 5%. The maintenance engineers can quantitatively evaluate the safety of anchored slope using the proposed technique.

2. REVIEW OF OTHER STUDIES

To overcome the shortcomings of lift-off test, many researchers and engineers tried to develop much more convenient as well as less expensive technique for evaluating the residual tensile load of anchor. Some of the previous studies are summarized in Table 2. The schematic diagram of anchor head is shown in Figure 1.

Table 2 Summary of previous research and their characteristics

Auhor (year)	Measurement part	Measuring method	Measuring principle (Physical phenomenon)	Physical quantity of interest
Mitsuishi K. *et al*. (2002) [7]	Extra part	Hammer blow Acceleration sensor	Change in vibration frequency of extra part (cantilever beam)	Hundres of Hz Vibration frequency
Takaue Y. *et al*. (2010) [8]	Nut or Bearing plate	Hammer blow Acceleration sensor	unknown	Thousands of Hz Vibration frequency
Harada N. *et al*. (2016) [9]	Extra part	Hammer blow Acceleration sensor	unknown	Thousands of Hz Vibration frequency
Hamasaki T. *et al*. (2019) [10]	Extra part	Hammer blow AE sensor	Change in vibration frequency of extra part (cantilever beam)	Hundres - Thousands of Hz Vibration frequency
Okubo K. *et al*. (2020) [11]	Tendon	Measurement of optical fiber embedded in tendon	Strain measurment using pulsed light	Amount of strain
Hisada H. et al. (2022) [12]	Fixer part	X-ray stress measurment method	Chenges in stress on bearing plate	Dozens of Mpa Stress

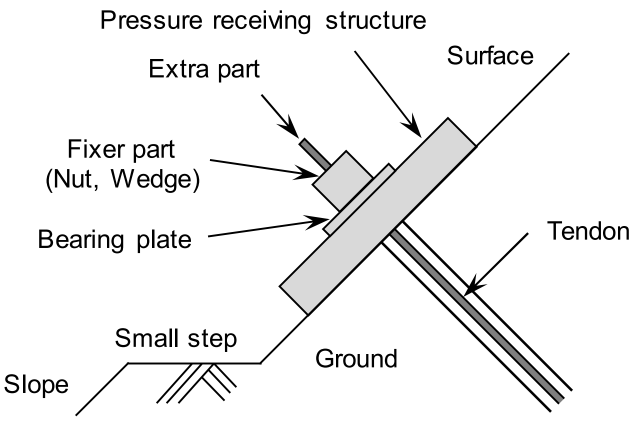


Figure 1 Schematic diagram of anchor head and tendon

Many studies tried to find the relationship between the resonance frequency of the anchor head and tensile load by hitting the extra part, nut or bearing plate. Frequency of interest varies from hundreds of Hz to thousands of Hz. Measuring principle and physical phenomenon of interest are not clear [7], [8], [9], [10]. Therefore, these method have not been implemented yet.

Okubo et al. [11] proposed the optical fiber sensing in which the optical fiber was glued to the anchor strand. Although the proposed technique has been in practice, the optical fiber should be installed in advance during construction. Therefore, it is impossible to apply this technique to the existing anchor without optical fiber.

Hisada et al. [12] proposed simple tension evaluation method using X-ray. They tried to estimate the residual tensile load based on the residual stress of the fixer part measured by X-ray irradiation. However, they concluded that the proposed method cannot replace the lift-off test.

3. PRINCIPLE OF VIBRATION METHOD AND MEASURING PROCEDURE

3.1. Principle of vibration method

The ground anchor consists of anchor body (fixing part), tendon tension part and anchor head as shown in Figure 2. We first assume that the tendon tension part of the ground anchor is approximated by a “string” fixed at both ends. If the tendon tension part is thin and long enough, the assumption of “string” is considered appropriate [13], [14]. Based on this assumption, the resonance frequency, f (Hz) of the free vibration of “string” in Figure 2 can be determined by line density, μ (kg/m), tension free length of the PC steel, L (m) and the operating tension, T (N) by Eq.1). Therefore, the residual tensile load can be determined by Eq.2).

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}} \quad \cdot\cdot\cdot 1)$$

$$T = 4L^2 f^2 \mu \quad \cdot\cdot\cdot 2)$$

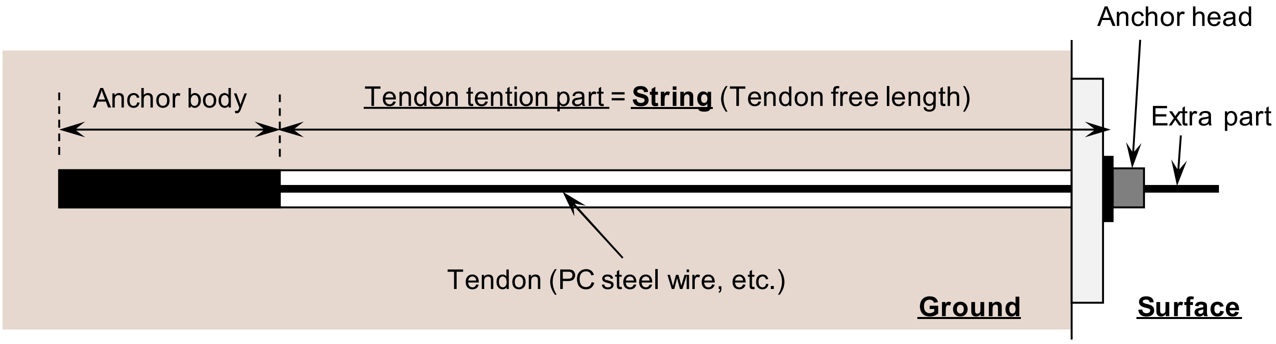


Figure 2 Schematic structure diagram of ground anchor

3.2. Measuring Procedure

The proposed method is performed with a small vibrator and accelerometers attached to the extra part of the anchor head. The schematic diagram of tensile load measuring system is shown in Figure 3.

We perform the proposed method by the following procedure. First, we place a small vibrator and accelerometers on the extra part of the anchor head. The waveform generated by the vibrator is a sweep waveform whose frequency of a sinusoidal wave increases continuously with time as shown in the upper part of Figure 4. The vibration is applied for 60 or 120 seconds with a frequency increase rate of 1 oct/min or less. In anchors with multiple steel wires, accelerometers are attached to the vibrated steel wire and the adjacent steel wires.

The lower part in Figure 4 shows an example of measurement data. We can easily understand the resonance frequency from the received waveform. We consider the measured resonance frequency as the natural frequency of the tendon tension part and calculate the residual tensile load by using Eq.2).

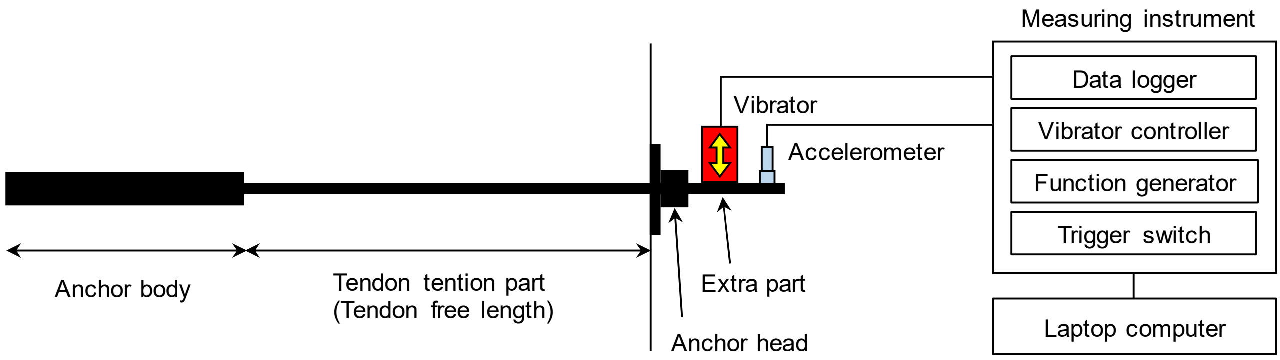


Figure 3 Schematic diagram of tensile load measuring system by vibration method

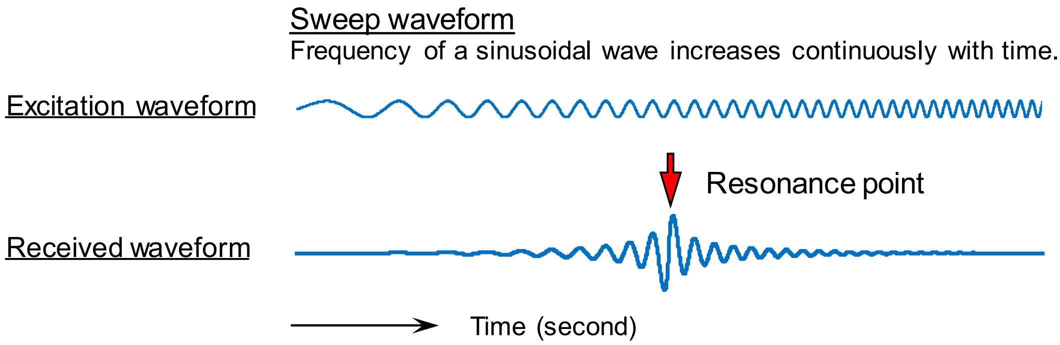
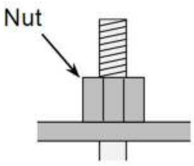
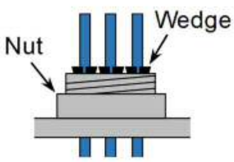
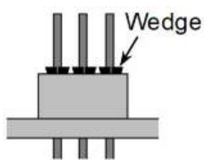


Figure 4 Schematic diagram of excitation / received waveform and resonance point

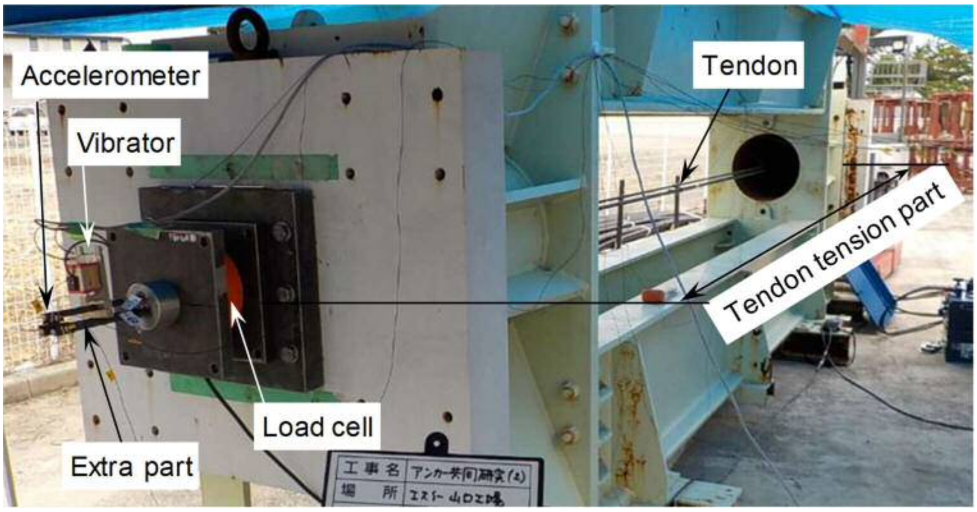
4. FULL SCALE MODEL EXPERIMENT

In order to confirm the tendon tension part can be approximated as "string", we carried out full scale experiments with three different type of anchors such as nut fixed type, wedge-nut fixed type and wedge fixed type. The basic properties of anchors are summarized in Table 3. The lengths of tendon tension part of different anchors are about 7 m. Its length is sufficiently long compared to the diameter of each steel wire. The experimental apparatus with 4,000 kN reaction force capacity is shown in Photograph 2. The center hole jack was equipped at one end and the accelerometer with vibrator was mounted on the extra length part of the other end of anchor. The small target was attached on the center part of tendon tension part to monitor the vibration acceleration of the tendon part of anchor directly by using the Laser Doppler vibrometer. The schematic view of the measuring system around the anchor head and the center of tendon part is also shown in Photograph 2.

Table 3 Anchors used for full scale anchor model experiment

Anchor standard	SEEE F60UA	SFL-3	VSL E5-3
Photo of anchor head			
Fixed type	 Nut	 Wedge+Nut	 Wedge
Number of strands	1	3	3
Strand diameter φ(mm)	21.8	15.2	12.7
T_{as} (kN)	343.8	469.8	329.4
T_{ys} (kN)	495.0	666.0	468.0

T_{as} : tendon allowable strength , T_{ys} : tendon yield strength



Photograph 2 Full scale anchor model (example of VSL E5-3)

The natural frequency vibration of tendon tension part with the length of about 7 m of different anchor type was first generated by hitting the tendon tension part with a rubber hammer. The free vibration generated by tapped with a rubber hammer was monitored by the Laser Doppler vibrometer. Observed and theoretical natural frequencies for different type of anchors with different tensile load are summarized in Table 4. The comparison between observed natural frequencies and theoretical natural frequencies calculated by Eq. 1) is shown in Figure 5. It is found that the observed natural frequency for all type of anchors coincides very well with the theoretical natural frequency over a wide range of tensile load. This means that the tendon tension part can be approximated as "string".

Table 4 Observed and theoretical values of tensile load and natural frequency

Anchor standard	Tensile load P_e (kN)			Tendon free length l_{sf} (mm)	Observed natural frequency f_m (Hz)	Theoretical natural frequency f_t (Hz)
	Set value conditions / set value (kN)		Observed value P_e (kN)			
SEEE F60UA	set	60.0	59.9	5872	13.1	13.2
	1/3 T_{as}	115.0	116.4	5878	17.8	18.5
	1/2 T_{as}	170.0	169.7	5883	21.2	22.3
	2/3 T_{as}	230.0	230.3	5887	24.4	25.9
	T_{as}	345.0	347.1	5898	29.7	31.8
	0.9 T_{ys}	445.0	444.9	5908	33.5	36.0
SFL-3	set	41.0	42.7	7225	8.2	7.9
	1/3 T_{as}	155.0	154.8	7238	15.7	15.0
	1/2 T_{as}	235.0	235.1	7246	19.5	18.4
	2/3 T_{as}	310.0	310.3	7253	22.5	21.2
	T_{as}	470.0	470.1	7268	27.8	26.0
	0.9 T_{ys}	600.0	600.1	7288	31.5	29.4
VSL E5-3	set	50.0	49.3	6853	10.4	10.6
	1/3 T_{as}	100.0	100.0	6862	14.6	15.1
	1/2 T_{as}	150.0	150.4	6868	17.8	18.6
	2/3 T_{as}	200.0	200.0	6874	20.4	21.4
	T_{as}	300.0	300.0	6885	25.0	26.2
	0.9 T_{ys}	400.0	100.4	6899	28.9	30.2

T_{as} : tendon allowable strength , T_{ys} : tendon yield strength

Finally, we tried to obtain the natural frequency of the tendon tension part by using a small vibrator and accelerometers attached to the extra part of the anchor head. An example of running spectrum and Fourier spectrum diagram is shown in Figure 6. It is found that the correct natural frequency of the tendon tension part was observed by the accelerometer attached to the extra part.

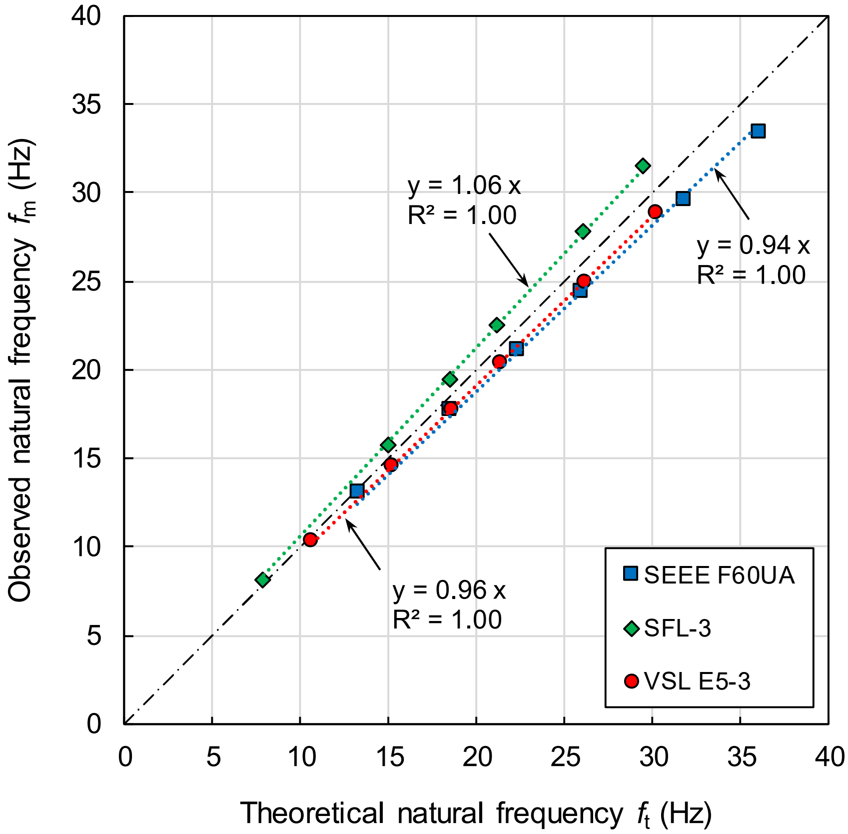


Figure 5 Comparison between observed and theoretical natural frequency

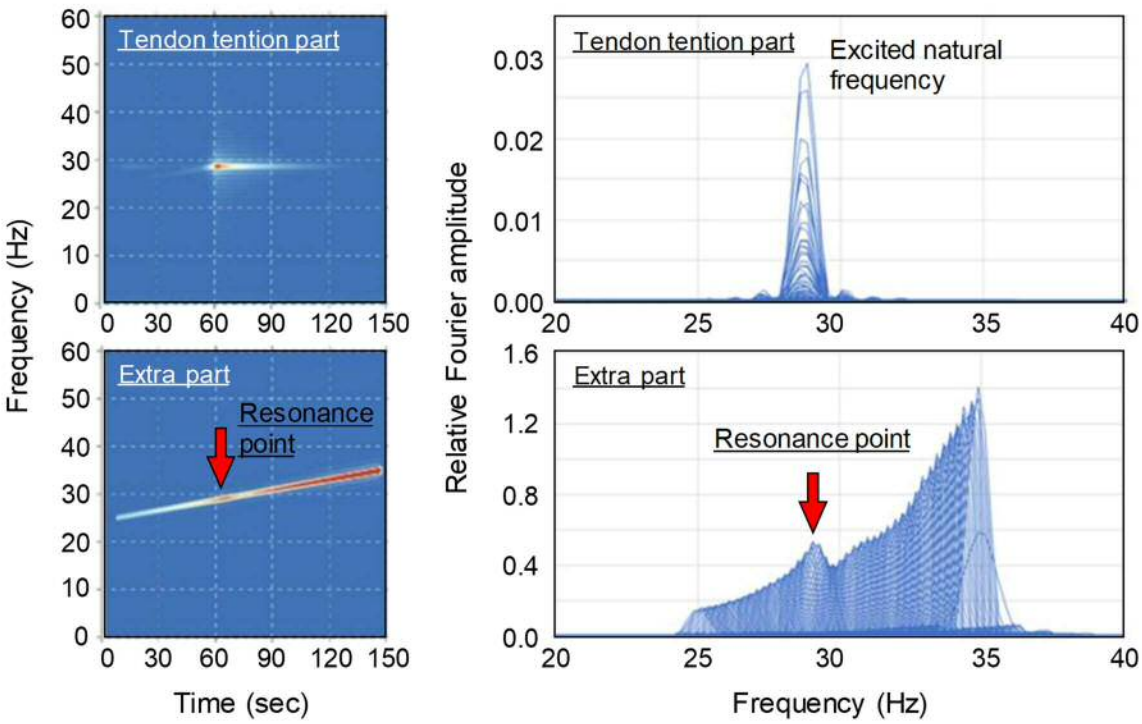


Figure 6 Example of running spectrum and Fourier spectrum diagram (VSL E5-3, 2/3 T_{as})

5. ON-SITE MEASUREMENT AND DISCUSSION

In order to confirm the validity of the vibration method, on-site measurements using the lift-off test and vibration method were conducted for existing ground anchors.

A total of 45 anchors were investigated on 14 slopes from A to N in Japan, as shown in Table 5. The tests were performed on the following seven types of anchors; SEEE, VSL, SHS, KP, FLO, SFL, and EHD. The tendon free lengths ranged from 4.0 to 16.0 m. Lift-off tests were performed on all anchors, and residual tensile loads were determined for 43 of these anchors. Anchors I-3 and I-4 did not "lift off" after 250 kN of tension loading, and no residual tensile load was determined because there was a risk that the anchor would break if we loaded it any further. The evaluation of soundness of anchor introduced in Table 1 is also shown in Table 5.

The residual tensile loads estimated from the vibration method (P) and measured by the lift-off test (P_e) are shown in Table 5, and the comparison of P_e and P is shown in Figure 7. The relationship between P_e and P is approximately 1:1, and the error of P with respect to P_e is within ±5% for 32 anchors and ±10% for 11 anchors at most. There is no systematic difference in error with respect to differences in anchor type or tendon free length.

In I-3 and I-4, where the residual tensile load could not be determined by the lift-off test, the residual tensile load higher than the maximum load in lift-off test was estimated by the vibration method. This method is characterized by its ability to safely estimate the residual tensile force even for such over-tensioned anchors.

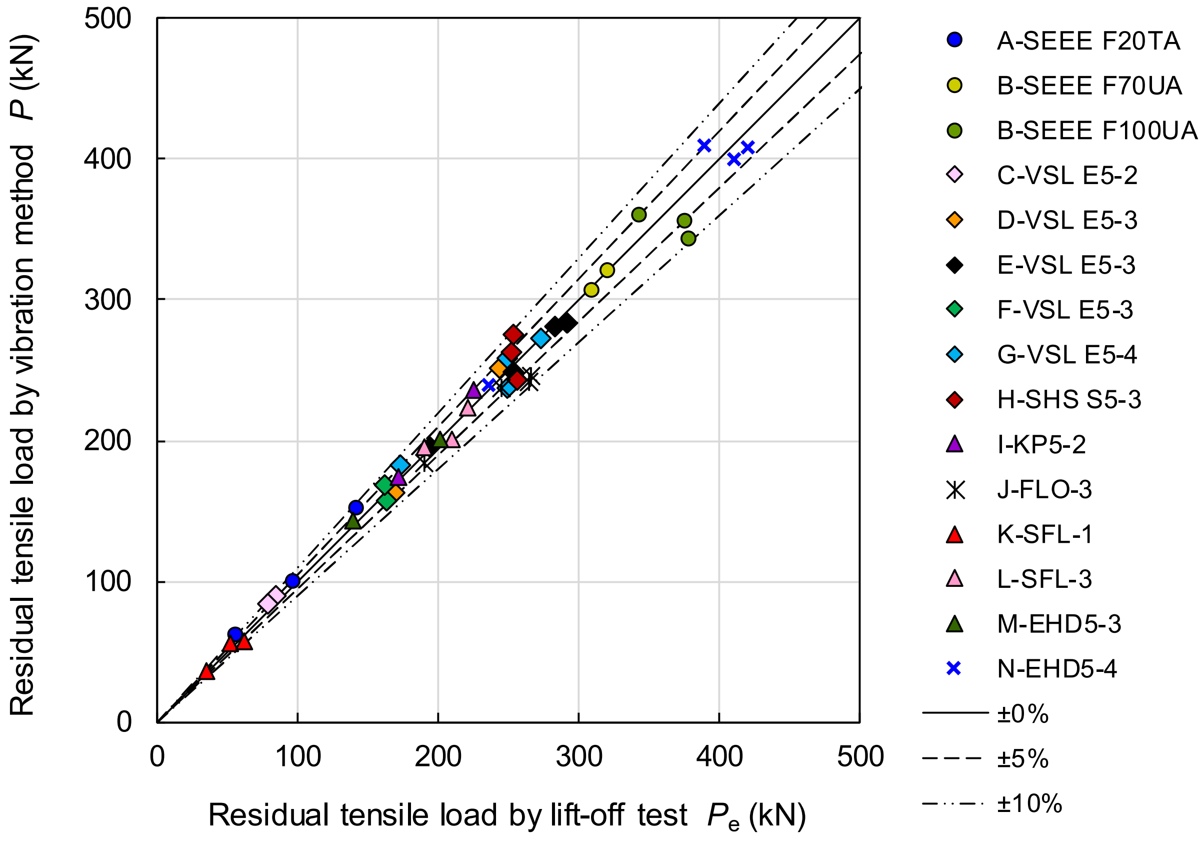


Figure 7 Comparison of residual tensile load obtained by lift-off test and vibration method

Table 5 Comparison of no-site measurement results of lift-off test and vibration method

Slope name	Anchor number	Anchor standard	Fixed type	Tendon free length l_{sf} (m)	Lift-off test		Vibration method			Error $(P-P_e)/P_e$ (%)
					Residual tensile load P_e (kN)	Evaluation	Resonance frequency f_m (Hz)	Residual tensile load P (kN)	Evaluation	
A	A-1	SEEE F20TA	Nut	7.6	57.0	B	15.0	61.0	B	7.0
	A-2	SEEE F20TA	Nut	7.6	98.0	A	19.6	100.0	A	2.0
	A-3	SEEE F20TA	Nut	10.6	142.0	A	17.0	151.0	A	6.3
B	B-1	SEEE F70UA	Nut	7.2	321.8	A	22.5	320.0	A	-0.6
	B-2	SEEE F70UA	Nut	7.2	310.0	A	22.2	306.8	A	-1.0
	B-3	SEEE F100UA	Nut	13.1	344.0	A	11.1	359.8	A	4.6
	B-4	SEEE F100UA	Nut	13.1	378.7	A	11.6	343.4	A	-9.3
	B-5	SEEE F100UA	Nut	13.1	376.6	A	11.6	356.0	A	-5.5
C	C-1	VSL E5-2	Wedge	8.5	85.0	B	14.1	89.0	B	4.7
	C-2	VSL E5-2	Wedge	8.5	79.0	B	13.7	84.0	B	6.3
D	D-1	VSL E5-3	Wedge	5.5	170.0	A	24.1	163.1	B	-4.1
	D-2	VSL E5-3	Wedge	4.0	243.2	A	41.1	251.6	A	3.5
E	E-1	VSL E5-3	Wedge	5.5	194.7	A	26.4	195.1	A	0.2
	E-2	VSL E5-3	Wedge	13.5	283.6	A	13.8	281.0	A	-0.9
	E-3	VSL E5-3	Wedge	9.5	253.7	A	17.2	249.1	A	-1.8
	E-4	VSL E5-3	Wedge	15.0	291.4	A	11.7	284.1	A	-2.5
F	F-1	VSL E5-3	Wedge	4.0	163.0	B	32.5	157.0	B	-3.7
	F-2	VSL E5-3	Wedge	4.5	162.0	B	29.9	168.0	A	3.7
G	G-1	VSL E5-4	Wedge	9.0	250.0	A	15.4	237.0	A	-5.2
	G-2	VSL E5-4	Wedge	8.5	274.0	A	17.5	273.0	A	-0.4
	G-3	VSL E5-4	Wedge	10.0	250.0	A	14.4	259.0	A	3.6
	G-4	VSL E5-4	Wedge	11.5	174.0	B	10.5	182.0	B	4.6
H	H-1	SHS S5-3	Wedge	13.5	256.0	A	12.0	243.5	A	-4.9
	H-2	SHS S5-3	Wedge	15.5	252.0	A	10.8	262.7	A	4.2
	H-3	SHS S5-3	Wedge	15.5	253.0	A	10.0	275.2	A	8.8
I	I-1	KP5-2	Wedge+Nut	7.5	225.0	B	26.0	236.0	B	4.9
	I-2	KP5-2	Wedge+Nut	7.5	172.0	A	22.4	174.0	A	1.2
	I-3	KP5-2	Wedge+Nut	7.5	>250	-	26.9	251.0	C	-
	I-4	KP5-2	Wedge+Nut	8.0	>250	-	26.8	284.0	D	-
J	J-1	FLO-3	Wedge+Nut	6.0	266.0	A	22.7	246.0	A	-7.5
	J-2	FLO-3	Wedge+Nut	6.0	265.0	A	22.5	242.0	A	-8.7
	J-3	FLO-3	Wedge+Nut	10.5	190.0	B	11.2	184.0	B	-3.2
	J-4	FLO-3	Wedge+Nut	13.0	245.0	A	10.3	238.0	A	-2.9
K	K-1	SFL-1	Wedge+Nut	7.5	52.0	B	15.0	56.0	B	7.7
	K-2	SFL-1	Wedge+Nut	13.0	62.0	B	8.8	57.0	B	-8.1
	K-3	SFL-1	Wedge+Nut	9.0	35.0	B	10.0	36.0	B	2.9
L	L-1	SFL-3	Wedge+Nut	8.0	210.0	B	15.4	201.0	B	-4.3
	L-2	SFL-3	Wedge+Nut	8.0	221.0	B	16.3	223.0	B	0.9
	L-3	SFL-3	Wedge+Nut	8.0	191.0	B	15.2	195.0	B	2.1
M	M-1	EHD5-3	Wedge+Nut	10.0	202.0	A	14.7	201.0	A	-0.5
	M-2	EHD5-3	Wedge+Nut	16.0	140.0	B	7.8	143.0	B	2.1
N	N-1	EHD5-4	Wedge+Nut	11.0	236.0	A	12.6	240.0	A	1.7
	N-2	EHD5-4	Wedge+Nut	11.0	411.0	A	16.3	400.0	A	-2.7
	N-3	EHD5-4	Wedge+Nut	9.5	421.0	A	19.1	408.0	A	-3.1
	N-4	EHD5-4	Wedge+Nut	14.5	390.0	A	12.5	409.0	A	4.9

6. ON-SITE INSPECTION WORK UNDER HEAVY TRAFFIC CONDITION

It is very difficult to close the road to traffic for on-site inspection work. We should carry out on-site inspection work under the heavy traffic condition with traffic lane regulation as shown in Photograph 3. We applied the proposed vibration method to the evaluation for residual tensile load of ground anchors installed in tunnel. The inspection work was carried out on the aerial work platform as shown in Photograph 3. If the lift-off test requires the temporary safety equipment under the heavy traffic condition, the lift-off test is sometimes impossible to carry out. On the other hand, the proposed technique can evaluate residual tensile load of anchor without the temporary and large equipment.

A total of 15 SEEE F70TA (nut fixed type) anchors were investigated. The tendon free lengths ranged from 11.8 to 15.3 m. There are 9 anchors on the driving lane side and 6 on the passing lane side. The sweep waveform vibration was applied to the extra part of anchor head for 60 seconds with a frequency increase rate of 1 oct/min or less.

Photograph 3 Application example of vibration method under heavy traffic condition

Table 6 Inspection result of vibration method under heavy traffic condition

Lane	Anchor number	Anchor standard	Fixed type	Tendon ultimate strength T_{us} (kN)	Tendon yield strength T_{ys} (kN)	Setting load P_t (kN)	Line density μ (kg/cm)	Tendon free length l_{sf} (m)	Observed resonant frequency f_m (Hz)	Residual tensile load P (kN)	P / P_t	Evaluation
Driving	207 L-2D	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.1	347.9	0.89	A
	211 L-3D	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	12.0	406.1	1.03	A
	216 L-1B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.4	365.7	0.93	A
	217 L-6A	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.9	401.4	1.02	A
	218 L-4A	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	10.8	333.6	0.85	A
	219 L-1A	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.3	360.0	0.92	A
	243 L-5A	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	11.8	15.8	421.4	1.07	A
	243 L-5B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	11.8	16.1	437.5	1.11	B
	244 L-1B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	11.8	15.3	392.6	1.00	A
Passing	201 R-5D	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.3	361.9	0.92	A
	207 R-1B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.8	392.0	1.00	A
	217 R-4B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.7	387.3	0.99	A
	218 R-4B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	13.2	493.2	1.26	C
	220 R-1A	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	15.3	11.2	354.2	0.90	A
	243 R-4B	SEEE F70TA	Nut	714.0	608.0	392.4	3.04	11.8	15.5	404.5	1.03	A

Measured resonance frequencies and estimated residual tensile loads for 15 anchors are summarized in Table 6. Residual tensile loads estimated by the vibration method ranged from 333.6 to 493.2 kN. Based on the anchor soundness guideline shown in Table 1, 13 anchors are evaluated to be “A” (Sound), 1 anchor to be “B” (Tendency to drop of soundness) and 1 anchor to be “C” (Possibility of dangerous situation).

To order to save the inspection time, three processes, “anchor cap removal”, “measurement” and “restoration work” were divided into three groups. The working time for 1 anchor was about 40 minutes. The total inspection work for 15 anchors took about 10 hours.

7. CONCLUSIONS

We have proposed a new method of non-destructive evaluation for residual tensile load of anchor by the “vibration method” based on the assumption of “string” of anchor tendon tension part. Based on a series of full-scale model experiments and on-site measurements for various type anchors conducted by using the proposed technique, the following conclusions were obtained.

(1) Based on full scale model experiments, the observed natural frequencies of tendon tension part for all type of anchors are found to coincide very well with the theoretical natural frequencies over a wide range of tensile load. This means that the tendon tension part can be approximated as “string” and the residual tensile load can be estimated by the equation “$T = 4\,L^2 f^2 \mu$ ”.
(2) The correct natural frequency of the tendon tension part can be observed by the accelerometer attached to the extra part.
(3) The sweep waveform vibration to the extra part of anchor head for 60 or 120 seconds with a frequency increase rate of 1 oct/min or less is effective to capture the resonance frequency of the tendon tension part. The combination of the running spectrum and Fourier spectrum diagram of the extra part vibration is recommended to clearly judge the resonance frequency of the tendon tension part
(4) Based on the on-site measurement for 45 anchors, the relationship between the residual tensile loads measured by the lift-off test (P_e) and the residual tensile loads estimated from the vibration method (P) is approximately 1:1, and the error of P with respect to P_e is within ±5% for 32 anchors and ±10% for 11 anchors at most.
(5) The lift-off test sometimes requires a temporary scaffold, safety equipment and typically requires time and costs. On the other hand, the proposed technique can evaluate residual tensile load of anchor without the temporary and large equipment. The maintenance engineers can quantitatively evaluate the safety of anchored slope using the proposed technique.

During the field measurement for 45 anchors, the resonance points are clearly seen as sharp spectral peaks for many anchors. On the other hand, there were some few data in which multiple peaks were observed and data in which the resonance point was unclear. In the future, standardization of the method for reading the resonance frequency will be necessary.

Also, we are studying whether it is possible to measure the residual tensile load with accuracy that does not cause practical problems even if the test is performed using a simplified procedure. If the tensile load can be measured in a short time by improving the procedure, the survey cost will be reduced and more anchors can be measured. That would facilitate sustainably maintaining infrastructure.

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REFERENCES

1. Okubo, K., Fujioka, K. and Takemoto, M. (2008). The maintenance of soil structure in the Expressway, Soil Mechanics and Foundation Engineering, Vol.56, No.2. pp2-3 (in Japanese)
2. Fujiwara, Y. and Sakai, T. (2016). A study of a lift-off test method for ground anchors, Journal of JSCE, Vol.4. pp106-117
3. Public Works Research Institute, Japan Anchor Association, Mie University, Nippon Expressway Research Institute Co., Ltd. (2020). Maintenance Manual for Ground Anchors, pp104-115 (in Japanese)
4. Central Nippon Expressway Co., Ltd. (2020). Survey Guidelines, pp ref. 2-12- ref. 2-25 (in Japanese)
5. Public Works Research Institute, Japan Anchor Association (2008). Maintenance Manual for Ground Anchor, pp13-75 (in Japanese)
6. Japan Highway Public Corporation (2002). Inspection and Soundness Survey Manual for Ground Anchors, pp1-18
7. Mitsuishi, K., Okada, H., Izakura, M., Tsukada, T. and Ohshima, W. (2002). The Development of The Method of Detecting The Anchor Tensile Force to The Impact Elastic Wave, The 47th Japanese Geotechnical Society Symposium Abstracts, pp7-14 (in Japanese)
8. Takaue, Y., Yoshimura, M., Kamata, T. and Uchida, S. (2010). Fundamental Resarc of Soundness Evaluation of Bolt Nut Type Ground Anchor Based on Impact Elastic Wave Method, The 65th Japan Society of Civil Engineers Annual Scientific Conference Abstracts, pp119-120 (in Japanese)
9. Harada, N., Kinoshita, E., Tsunekawa, Y., Takanashi, T., Sakamoto, H. and Suzuki, K. (2016). Estimation Method for Both Residual Tensile Force and Fixation Lenfth of Ground Anchor under Slopes, The 55th Japan Landslide Society Annual Scientific Conference Abstracts, pp151-152 (in Japanese)
10. Hamasaki, T., Kasama, K., Matsunaga, T., Ogawa, R., Isobe, Y. and Sayama, M. (2019). Experimental Study for Estimating Tension Force of Ground Anchors by Hammering Technology, Journal of Japan Society of Civil Engineers, Division C (Geotechnics), Vol.75, No.1. pp90-102 (in Japanese)
11. Okubo, K., Imai, M., Sogabe, N., Tobe, H., Nakaue, S., Hayakawa, M. and Niwa, J. (2020). Application of The Measuring Method for Tensile Force Distribution by Optical Fiber to Ground Anchor, Journal of Japan Society of Civil Engineers, Division C (Geotechnics), Vol.76, No.1. pp126-138 (in Japanese)
12. Hisada, H., Tayama, S., Fujiwara, Y. and Fujitomo, T. (2022). Field Applicability Verification of Ground Anchor Tension Evaluation Method Using X-Rays, The 77th Japan Society of Civil Engineers Annual Scientific Conference Abstracts, ppIII-202 (in Japanese)
13. Saito, H., Yamazaki, M., Yashima, A., Nawa, K., Aoike, K. and Sone, Y. (2021). Estimation of Ground Anchor Residual Tension by Vibration Method. Journal of Japan Society of Civil Engineers, Division C (Geotechnics), Vol.77, No.3. pp213-232 (in Japanese)
14. Nawa, K., Yashima, A., Murata, Y., Kariya, K., Saito, H., Aoike, K., Sone, Y. and Yamazaki, M. (2021). Evaluation of Ground Anchor Residual Tension by Vibration Method, Proc. CREST2020, pp271-282