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Special Contribution

The challenge to Structural Health Monitoring of Expressway Embankment

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1. Introduction

Structural Health Monitoring (SHM) is a method of evaluating and monitoring structural health. SHM has been widely applied in various engineering structures such as bridges and buildings. On the other hand, there are some unresolved issues in applying SHM to expressway embankments, namely

A) Appearance check cannot evaluate the soundness of road embankment if there is no deformation or damage.
B) Borehole investigation cannot evaluate the overall soundness of road embankment.
C) Embankment is not constructed based on mechanical properties (stiffness & strength).
D) Change in the soundness of road embankment is not monitored continuously.
E) Extension of the road embankment is long. Monitoring road embankments in service is difficult.

Collapses of road embankments due to heavy rain or earthquake often close transportation and resulted in serious damage in the community (see Fig. 1). Therefore, it is necessary to assess the current soundness and predict the future soundness of road embankment. Fig. 2 shows the typical curves which explain the different changes in the soundness of road embankment with time [1]. The change in the soundness of road embankment depends on “initial condition” and “subsequent factors”. In this research project, some challenges have been done to solve the unresolved issues mentioned above.

Fig. 1. Collapses of road embankment due to heavy rain or earthquake

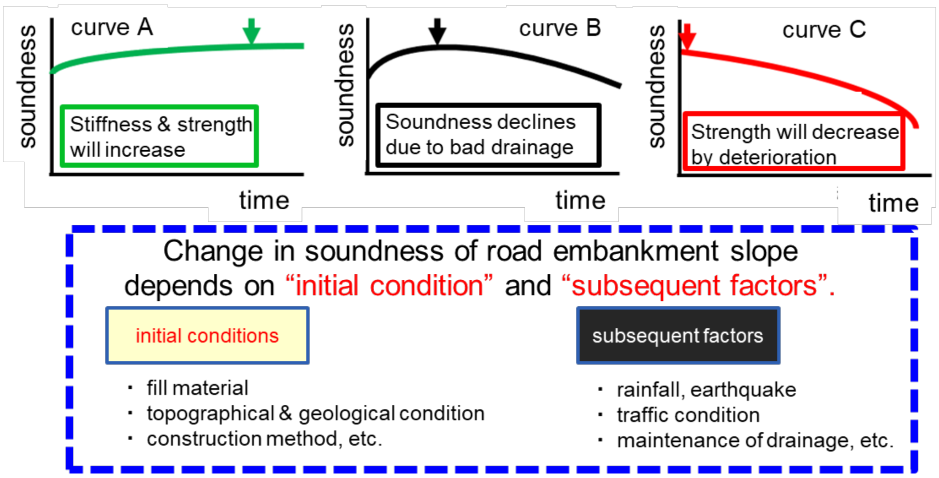

Fig. 2. Change in soundness of road embankment with time

2. Geophysical exploration techniques for inspection

In order to evaluate the initial mechanical property and the change in the soundness of expressway embankment and to survey the expressway embankment efficiently under the heavy traffic condition, the following geophysical exploration techniques were applied in this research project, namely

1) 2-dimensional (2-D) surface wave exploration
2) Electric resistivity exploration
3) Passive linear array exploration
4) Distributed Acoustic Sensing (DAS)

Newly designed carts were manufactured to save inspection time. Photo 1 shows the cart with geophones for 2-D surface wave and passive linear array explorations [2], [3].

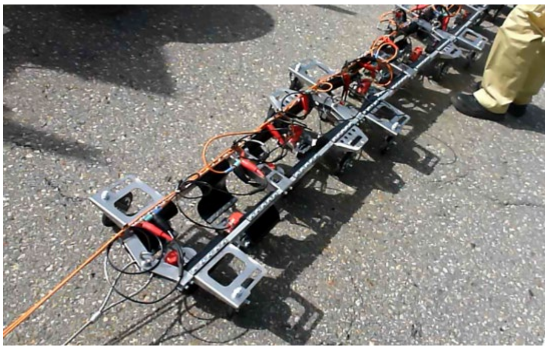

Photo 1 Cart with geophones

3. Evaluation of initial mechanical property of expressway embankment

The initial condition of the expressway embankment depends on fill material, topographical and geological conditions, construction methods, etc. However, the expressway embankment was not constructed based on mechanical properties such as stiffness and strength but relative density, at least in Japan. Therefore, the initial stiffness and strength of the expressway embankment are unknown. In this chapter, the initial mechanical property of the expressway embankment was evaluated [3].

Geophysical exploration inspection works were carried out on the newly opened sections of four expressways such as Tokai-Hokuriku expressway, Shin-Tomei expressway, Shin-Meishin expressway and Tokai-Kanjo expressway in Aichi, Mie and Gifu Prefectures in Japan. The locations of the inspection works are shown in Fig. 3. The electric resistivity exploration inspections were carried out in addition to 2-D surface wave exploration on Shin-Meishin expressway and Tokai-Kanjo expressway.

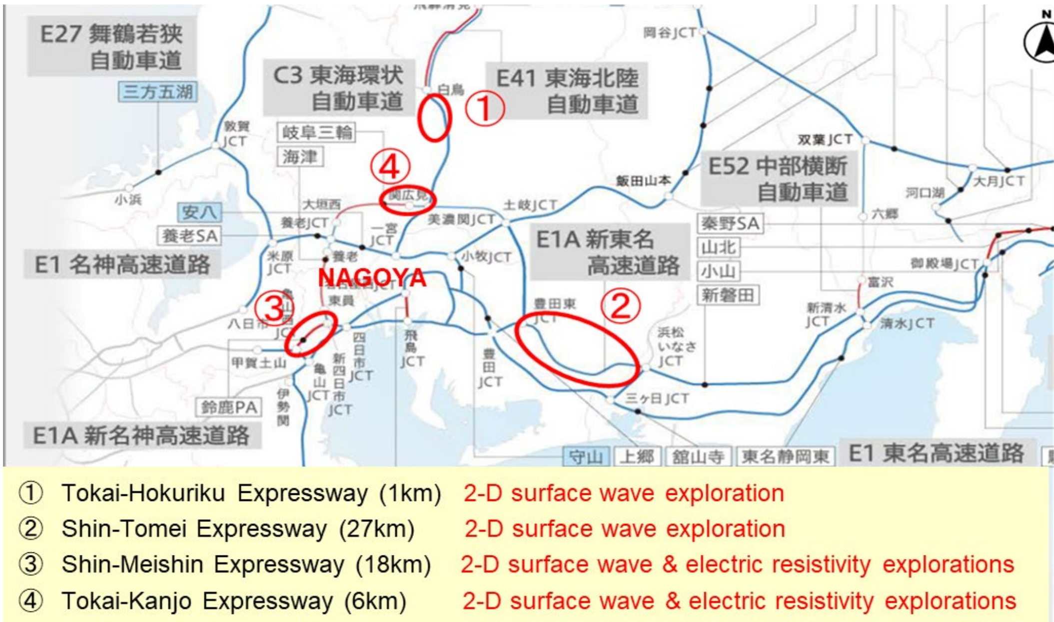

Fig. 3. Locations of the inspection works for four expressways

The distribution of the shear wave velocity for Tokai-Hokuriku expressway from the road surface down to the depth of 20 m is shown in Fig. 4. It is found that low shear wave velocities are observed around the fill/cut boundary and close to the box culvert. The distribution of the shear wave velocity for some extensions of Shin-Tomei expressway is also shown in Fig.5. The difference between the shear wave velocity for the fill section and cut section is easily understood. The shear wave velocity around the embankment slope surface is found to be low.

The following findings were obtained from geophysical exploration inspection works for the newly opened sections of four expressways,

1) Initial shear wave velocity differs depending on the fill material and topographical condition of the foundation

ground.
2) Initial low shear wave velocities are observed around the fill/cut boundary and embankment slope surface, and close to the underground structure.
3) Initial shear wave velocity in the embankment can be evaluated from the stiff pavement.
4) Initial water content in the embankment can be estimated by the electric resistivity exploration.
5) The exploration speed increased dramatically by introducing FWD (Falling Weight Deflectometer) impact. The FWD impact improves the S/N ratio for 2-D surface wave exploration.

Therefore, it is possible for engineers to narrow down weak points requiring future inspection based on the initial inspection results.

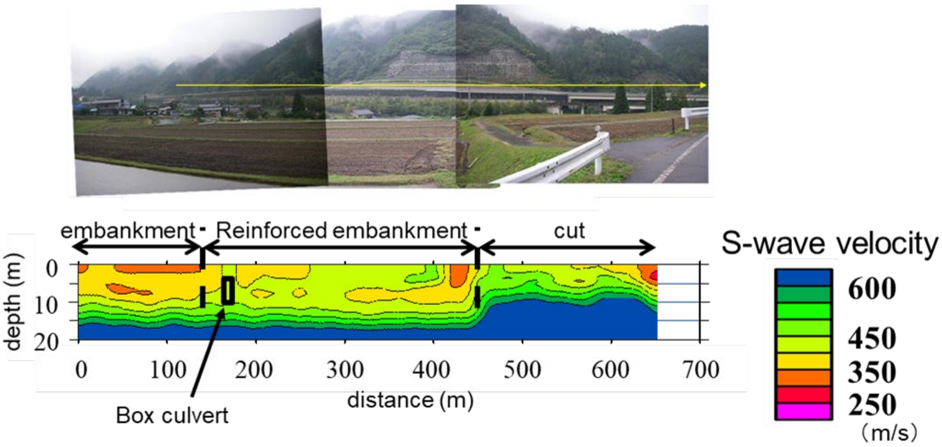

Fig. 4. Distribution of the shear wave velocity of road embankment for Tokai-Hokuriku expressway

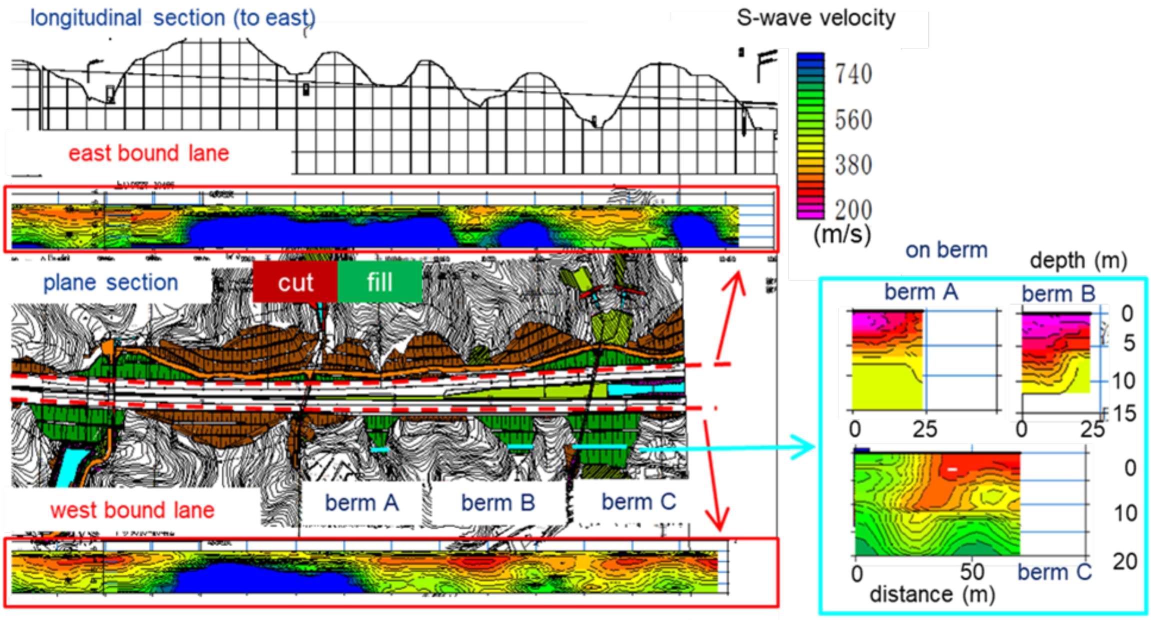

Fig. 5. Distribution of the shear wave velocity for some extension of Shin-Tomei expressway

4. Change in shear wave velocity with time

In order to predict the change in the soundness of the expressway embankment, continuous (or scheduled) monitoring is needed. In this chapter, the initial and subsequent mechanical properties obtained by geophysical exploration along the road embankment were compared. The target road embankment is located on Tokai-Hokuriku Expressway in Gifu Prefecture. The initial inspection result obtained in 2008 was shown in the previous chapter. Subsequent 2-D surface wave exploration was carried out for the same extension of Tokai-Hokuriku Expressway in 2020.

Fig.6 shows both the distribution of the shear wave velocity for the same extension of Tokai-Hokuriku expressway obtained in 2008 and that obtained in 2020. Fig.7 is also prepared to easily understand the change in the shear wave velocity for the same extension. The change rate is defined by (B-A)/A×100 (%), in which A is the shear wave velocity obtained in 2008 and B is that obtained in 2020. It is found from these figures that a large drop in the shear wave velocity was observed around the fill/cut boundary. This area corresponds to repair marks on the pavement. This means that the area where a large drop in the shear wave velocity with time is observed should be carefully inspected and maintained. It is also possible for engineers to understand the soundness degradation even if there is no deformation or damage.

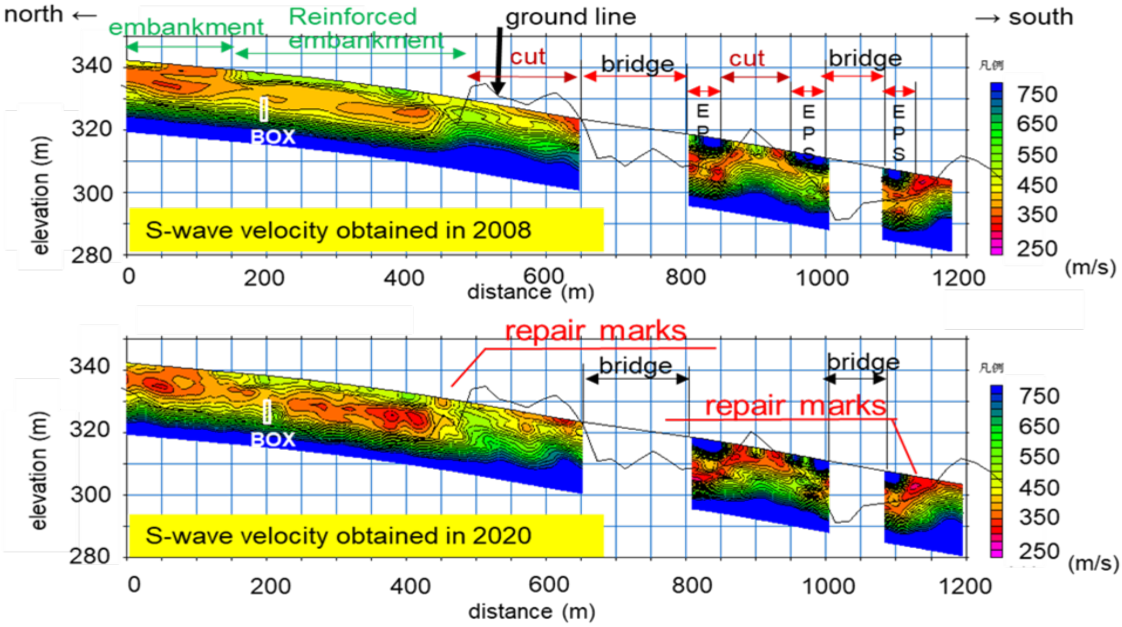

Fig. 6. Inspection results obtained in year 2008 and 2020

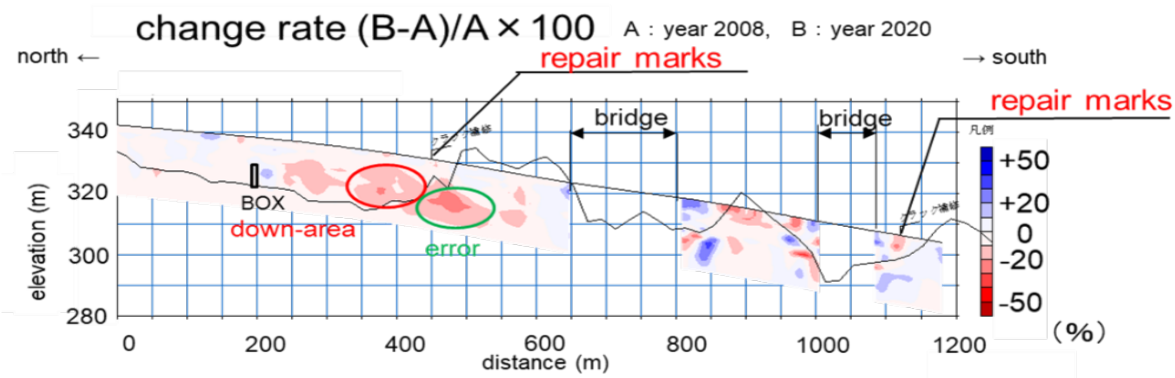

Fig. 7. Change in shear wave velocity for same extension

5. Passive linear array exploration

The heavy vehicle vibration reduces S/N ratio for 2-D surface wave exploration and the exploration efficiency on expressways. Active surface wave exploration can evaluate the shear wave velocity down to about 20m. There are many high expressway embankments with more than 20m. Therefore, we would like to carry out the inspection work efficiently under the heavy traffic condition and evaluate the shear wave velocity in the embankment deeper than 20m from the road surface. To satisfy these requests, the passive linear array exploration technique was applied [4].

Photo 2 Target embankment with damage

First target embankment is located on Shin-Tomei expressway in Shizuoka Prefecture. The embankment fill material is mad stone. The embankment height is about 27m. On the embankment slope, lots of spring water and damages of drainage facility were observed as shown in Photo 2. These damages are thought to be partially due to the abundant groundwater in the embankment and the embankment settlement.

The procedure of the passive linear array exploration is as follows, namely

1) 12 carts were connected at 5m intervals.
2) Vibrations induced by heavy vehicles were monitored for 6 minutes.
3) Move all carts 30m. Monitor vibrations again for 6 minutes.
4) Repeat movement and measurement.

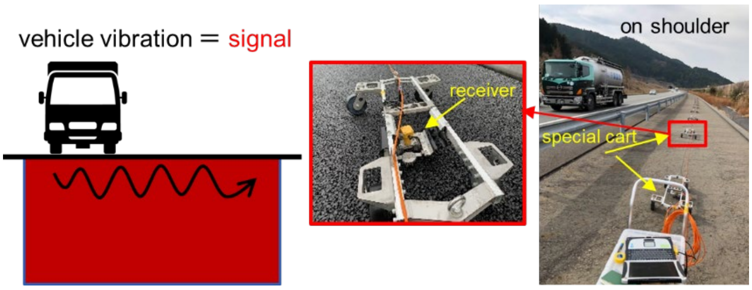

Fig. 8. Actual condition of passive linear array exploration

Fig.8 shows the actual condition of the field inspection.

The inspection result by the passive linear array exploration is shown in Fig.9. It is found that the passive linear array exploration can evaluate the distribution of shear wave velocity from the ground surface down to about 30m under heavy traffic condition. The region with low shear wave velocity and low electric resistivity corresponds to the area where spring water, gaps of drainage ditch and cracks of cover concrete were observed.

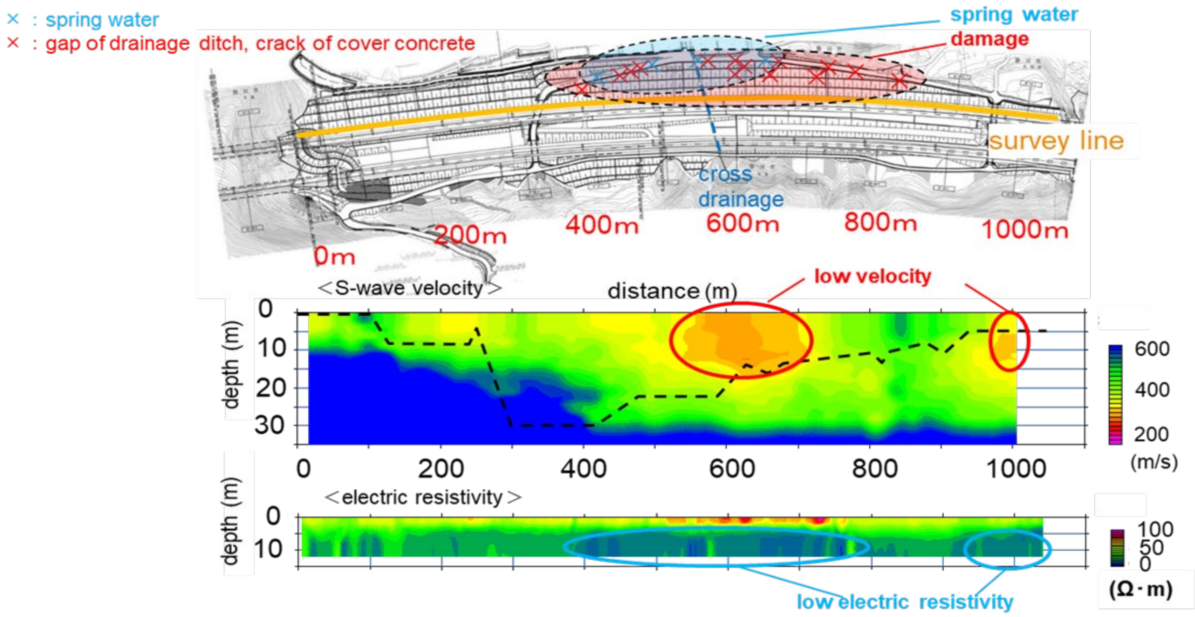

Fig. 9. Inspection result by the passive linear array exploration for Shin-Tomei expressway

Second target embankment is located on Chuo expressway in Nagano Prefecture. The embankment slope surface collapsed in a certain section some years ago. The same inspection procedure as Shin-Tomei expressway was employed. The inspection result by the passive linear array exploration is shown in Fig.10. It is found that the low shear wave velocity area corresponds to the damaged area where the embankment slope surface collapsed some years ago.

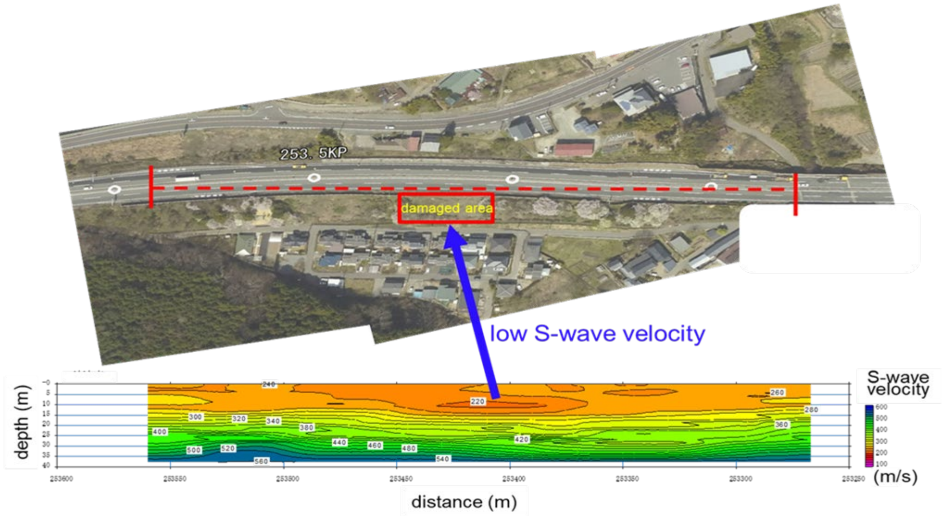

Fig. 10. Inspection result by the passive linear array exploration for Chuo expressway

6. Distributed Acoustic Sensing (DAS)

Geophysical explorations introduced in the previous chapters often demands the regulation of road traffic. In order to prevent such regulations, alternative monitoring techniques which enable remote measurement or use existing infrastructure should be developed. One candidate satisfying this request is the Distributed Acoustic Sensing (DAS) using existing optical fiber [5], [6]. If we have subsurface telecom optical fibers under the pavement of embankment, we can utilize it as DAS (see Fig.11). DAS measurement can be carried out from the hand hole on the pavement under the traffic regulation condition. On the other hand, the measurement from the road maintenance office does not require the traffic regulation. This is a big advantage.

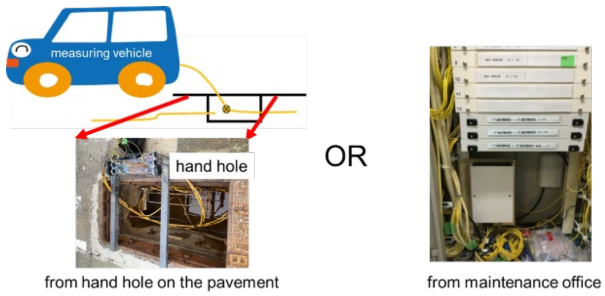

Fig. 11. DAS using optical fiber

The comparison of the inspection result by the passive linear array exploration with geophones with the traffic regulation and that by DAS with the subsurface telecom fiber is shown in Fig.12. It is found that the shear wave velocity distribution measured by DAS is very similar to that by the passive linear array exploration with geophones. However, it is necessary to improve DAS measurement technology for bringing DAS accuracy and resolution closer to the result by the passive linear array exploration with geophones in the future.

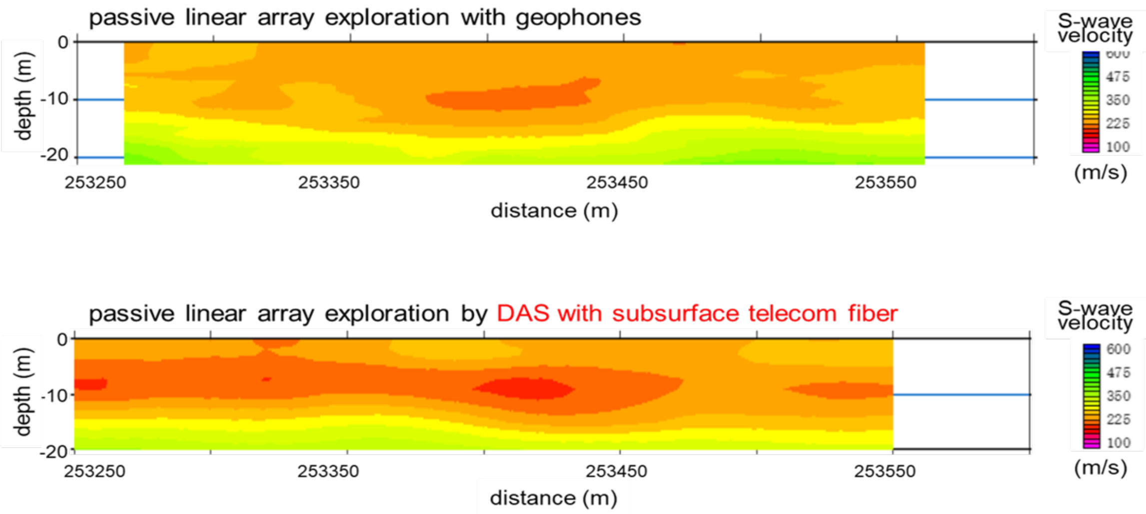

Fig. 12. Comparison of the inspection result by passive linear array exploration and DAS

7. Conclusions

Some challenges have been done to solve the unresolved issues in applying Structural Health Monitoring (SHM) to expressway embankments. Based on field inspections for different expressway embankments, the following conclusions were obtained.

1) Geophysical explorations can evaluate the initial stiffness and electric resistivity of expressway embankments. It is possible for engineers to narrow down weak points requiring further inspection based on these inspection results.
2) If a large drop in the shear wave velocity with time is observed at some area, that area should be carefully inspected further and maintained. Engineers can understand the soundness degradation based on the drop in the shear wave velocity with time even if there is no deformation or damage.
3) Passive linear array exploration can evaluate the overall stiffness of expressway embankments under heavy traffic conditions.
4) Geophysical explorations introduced often demands the regulation of road traffic. In order to prevent such regulations, alternative monitoring techniques which enable remote measurement or use existing infrastructure should be developed.
5) DAS measurement from the road maintenance office does not require traffic regulation. However, it is necessary to improve DAS measurement technology for bringing DAS accuracy and resolution closer to the result by the passive linear array exploration in the future.

Acknowledgments

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◆ A brief CV of Prof. Atsushi Yashima

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