SEISMIC VULNERABILITY INDICES FOR GROUND AND STRUCTURES USING MICROTREMOR

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Summary

Earthquake disaster never occurs whenever seismic force does not surpass durability of ground and structures. Thus continuous watch of earthquake motion is first of all necessary, in order to predict and monitor the occurrence of earthquake disaster. For the ground and structures exposed to earthquake motion, it is necessary to grasp their durability precisely by executing investigations in advance. From the view point of earthquake disaster prevention, to grasp the durability of ground and structures is even more important than to monitor the earthquake motion.

In this paper, a new technique to investigate rapidly with precision durability against earthquake of various structures and surface ground by using microtremor. Validity of the proposed method has been examined by comparing the results of investigations by the new technique in the earthquake damaged areas (before or after the event) with actual earthquake damage experienced.

If weak points of structures can be detected in advance by investigating the durability of various structures and ground, damage of structures can be decreased by taking appropriate countermeasures. Besides, secondary disaster can be also decreased very much by adopting precise immediate measures based upon accurate damage estimation when earthquake occurs.

Key Words: Vulnerability indices, K-values, microtremor, earthquake, QTS, damage, spectral ratio H/V, surface ground, viaduct, embankment, derailment/overturn

Introduction

To increase the durability of ground and structures beyond the presumed seismic force is fundamental of earthquake disaster prevention. However, although enough durability existed initially, it may decrease under presumed seismic force due to deterioration in time. In very cold weather area or very much rain fall area, durability of ground changes by seasons. Then to grasp precisely durability “at present” becomes fundamental to disaster prevention. For the structures without enough durability due to deterioration in time or by past earthquake, it is necessary to reinforce the weak points. New structures, of course, must be constructed with sufficient durability.

It is important to investigate in advance whether ground and reinforced old structures or newly constructed structures are furnished with prescribed resistant power or not. If such initial dynamic characteristics are grasped, maintenance can be performed rationally and damage extent will be quantitatively estimated.

Damaged points due to earthquake motions are weak points revealed by earthquake itself. If weak points are investigated in advance, it is possible to reinforce the structures before receiving damage by earthquake. In case of railway structures, if the weak point does not hinder train operation, it can be utilized as a monitoring point of earthquake damage occurrence. In addition, if seismic characteristics of ground and structures are already known, seismic intensity distribution of the area can be precisely estimated.

Occurrence of earthquake damage depends upon strength, period and duration of seismic motions. These parameters, of course, depend upon earthquake itself but they are also strongly influenced by the seismic response characteristics of surface ground and structures. Thus, the weak points can be found by investigating seismic characteristics of surface ground and structures.

Estimation of Seismic Characteristics of Ground and Structures

It is expected to increase the precision of damage estimation remarkably, if seismic characteristics of surface ground affecting earthquake damage can be grasped not by boring but by precise measurement. Characteristics of surface ground can be approximated by spectral ratio of horizontal to vertical component (QTS: Quasi-Transfer Spectrum) of microtremor (Nakamura, 1989).

Seismic response characteristics of structures can be estimated by spectral ratios of microtremors measured simultaneously on structures and their foundation ground surface. QTS of microtremors on the structures are approximated by combined characteristics of ground and structures.

The results of microtremor measurements at every 100 m along railway lines are arranged as procedure sheets for disaster prevention. It suggests good correspondence of QTS of microtremors with geological and topographic structures. Until now microtremors of grounds and structures at more than 20,000 points along railway lines and elsewhere have been measured. In 1995 and 1996, microtremors of ground and structures were observed in total at nearly 3,000 points in and near Kobe city after the 1995 Hyogo-Ken-Nanbu Earthquake.

Vulnerability Indices of Ground and Structures (K-values)

Vulnerability indices (K-values) derived from strains of ground and structures in time of earthquakes are proposed as follow.

a) Ground

For ground, shear strain γ of surface ground is noticed. Table 1 shows relationship of γ to ground disasters compiled by Ishihara (1978). It indicates that from $\gamma \cong 1000\times10^{-6}$ ground begins to show non-linear character and in $\gamma > 10{,}000\times10^{-6}$ large deformation and collapse occur.

Table-1 Strain Dependence of Dynamic Properties of Soil

Size of Strain γ	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
Phenomena	Wave, Vibration		Crack, Settlement		Landslide, Soil Compaction, Liquefaction	
Dynamic Properties	Elasticity		Elasto-Plasticity		Collapse	
					Repeat- Effect, Speed- Effect of Loading	

Simplifying the shear strain deformation of surface ground as shown in Figure 1, average shear strain γ of surface ground can be estimated by following formula, namely

$$\gamma = A_g \times d/H \qquad (1)$$

where, A_g is amplification factor, H is thickness of surface layer, and d is seismic displacement of the basement ground.

Putting S-wave velocities of basement ground and surface ground as v_b and v_s respectively, proper predominant frequency F_g of surface ground is approximately expressed as

$$F_g = v_b/(4A_g \times H) \qquad (2)$$

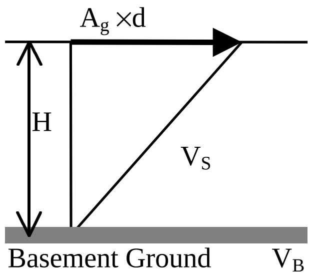

Fig.1 Surface Ground Strain

Acceleration of basement ground α_b is expressed as

$$\alpha_b = (2\pi F_g)^2 \times d$$

and γ is expressed by F_g, A_g and v_b as follows:

$$\gamma = (A_g \times \alpha_b/(2\pi F_g)^2) \times (4A_g \times F_g/v_b)$$
$$= (A_g^2/F_g) \times (\alpha_b/(\pi^2 v_b)) \qquad (3)$$

If efficiency of applied dynamic force is assumed to be e % of static force, effective γ_e is

$$\gamma_e = K_g(e) \times \alpha_b \qquad (4)$$
$$K_g(e) = e \times (A_g^2/F_g)/(\pi^2 v_b)/100. \qquad (5)$$

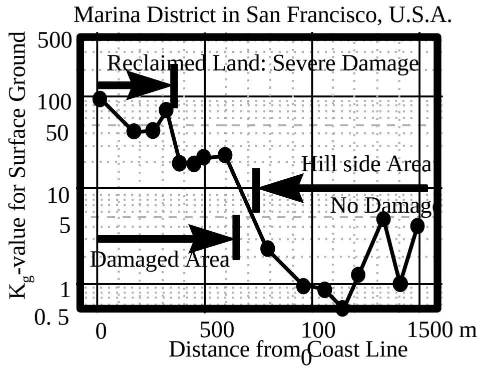

Fig. 2 K_g-values derived from QTS of Microtremor in S.F.

The value of v_b is expected to be nearly constant in a broad area and K_g is a proper value for measured point. Thus K_g can be considered as an index to indicate easiness of deformation of measured points which is expected useful to detect weak points of the ground.

As we can consider v_b = 600 m/s, we obtain $1/(\pi^2 v_b) = 1.69 \times 10^{-6}$ (s/cm). If we put e = 60 %, then $K_g(e) \cong A_g^2/F_g$ and the effective strain can be estimated by multiplying $K_g(e)$ value with maximum acceleration of basement ground in Gal (= cm/s^2).

Figure 2 indicates K_g-values obtained in San Francisco Bay Area after the 1989 Loma-Prieta Earthquake. For Marina district the result along a line from sea coast to hillside is shown. It shows K_g at the sites where grounds deform much are bigger than 20 and K_g at the sites with no damage are very small. Considering the maximum basement accelerations around the area are estimated as 50 Gal based on observations, $K_g = 1000 \times 10^{-6}$ separates the areas liquefied or not.

b) Embankment

In the past, embankment was most common railway structures which roughly occupied 80 % of all railway lines in Japan. Thus to grasp seismic characteristics of embankment is very important for the earthquake disaster prevention of railways. We found it is rather easy to obtain characteristics of embankment body and its foundation grounds separately by measuring microtremors on the embankment and on the ground surface under the embankment simultaneously. Vulnerability indices of embankment body and its foundation ground can be estimated separately and originated strains can also be calculated. Thus, it is expected possible to discriminate the damage due to surface ground deformation and collapse of embankment body itself. In addition, from the microtremor measurements on the embankment alone vulnerability indices of the structures consisting of embankment and surface ground together can be simply calculated. Embankment can be considered as a local additional surface layer and vulnerability index K_j for the embankment and surface ground together can be defined as K_g defined for the surface ground when e = 60 %, namely,

$$K_j = A^2/F, \qquad (6)$$

where F and A are predominant frequency and its amplification factor obtained from QTS of microtremors observed on the embankment.

Embankments between Kayanuma and Gojikkoku along Sen-mou Line (Kushiro-Abashiri line in Hokkaido, Japan) were damaged by the 1994 Hokkaido-Toho-Oki Earthquake again after the damaged parts by the 1993 Kushiro-Oki Earthquake were repaired. Microtremors were measured on the shoulders of both sides of the embankments damaged by the 1993 Kushiro-Oki Earthquake and K_j values were calculated. After the measurements the 1994 Hokkaido-Toho-Oki Earthquake occurred and the measurement was considered as that before earthquake.

Figure 3 shows comparison of K_j-values obtained before the earthquake in 1994 and the damage degrees. It shows places with large K_j-values correspond to the sites with big damage. Besides, K_j-values of left and right sides of the embankment show big difference and the damage of the 1994 Hokkaido-Toho-Oki Earthquake (subsidence of embankment) was severe, where K_j-values were larger, which suggests that K_j-values represent the vulnerability precisely.

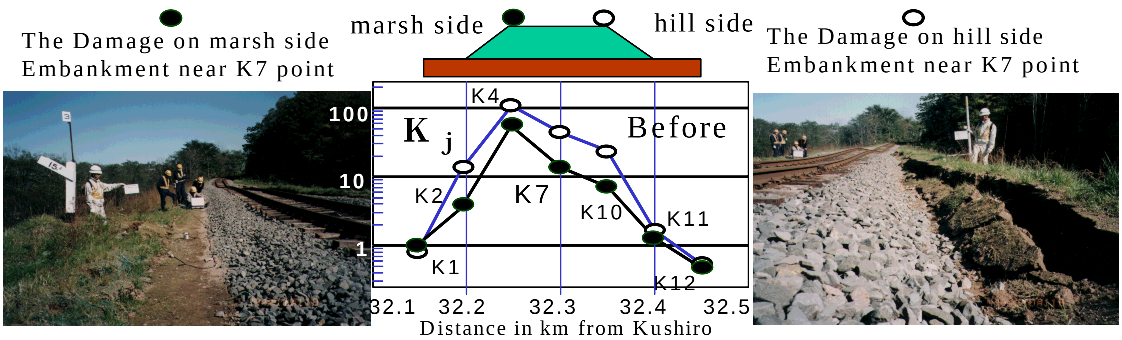

Fig. 3 Relation between Embankment Damage and K_j-values measured before the earthquake

c) Rigid Frame Viaducts

Rigid frame viaducts have become common now as railway structures. Earthquake damage of rigid frame viaduct has occurred since many years ago. Concrete cover of upper and lower column ends of the viaducts were peeled off and inner-reinforcing iron rods were exposed. In addition, middle layer beams of the viaducts of Shinkansen received big cracks. Near the damaged viaducts of Keihin-kyuko Line and Tsugaru-Kaikyo Line, alarm seismometers were installed and maximum seismic accelerations around 200-300 Gal were recorded. The 1995 Hyogo-Ken-Nanbu Earthquake recorded acceleration bigger than 500 Gal (nearly twice of ever experienced seismic acceleration until then) and fatal collapse occurred. Some viaducts suddenly collapsed by shear failures which essentially cannot be expected to occur before bending failures. Other viaducts collapsed fatally by gradual large bending failures.

In general, concrete structures are designed as bending failures precede at first and vulnerability index K_{sg} is here defined by noting marginal strains which appear at the upper and lower column ends. Basic idea is to calculate the marginal strains ε of upper and lower column ends by multiplying K_{sg} and maximum seismic acceleration α of basement ground or of surface ground together.

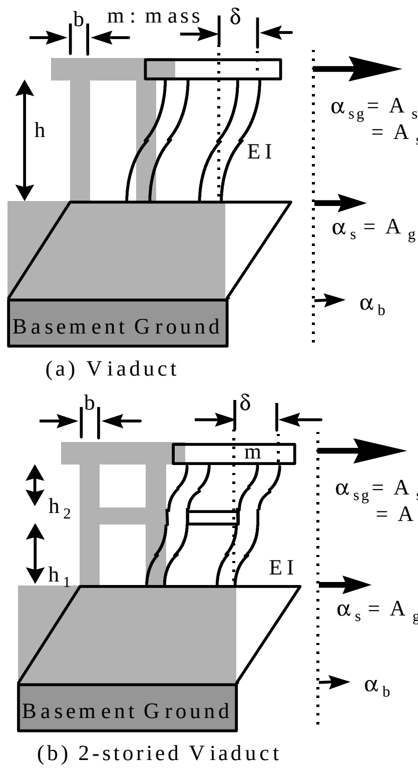

Fig. 4 Deformation of Viaduct

At first, bending deformation of the viaduct is calculated by applying acceleration α multiplied by combined amplification factor of surface ground and viaduct or by amplification factor of viaduct itself.

According to Figure 4, bending deformation δ of a viaduct against seismic inertia force is as follow.

$$\begin{aligned}\delta &= m\times\alpha/k\\ &= A_{sg}\times\alpha_b/(2\pi F_s)^2 = 1/(4\pi^2)\times(A_{sg}/F_s^{\,2})\times\alpha_b\\ &= A_s\times\alpha_s/(2\pi F_s)^2 = 1/(4\pi^2)\times(A_s/F_s^{\,2})\times\alpha_s\end{aligned}$$

Then marginal strains ε of upper and lower column ends are estimated from bending deformation with characteristics and size of the viaduct.

$$\begin{aligned}\varepsilon &= \sigma/E\\ &= (M/(EI))\times(b/2)\\ &= (6EI/h^2)\times\delta/(EI)\times(b/2)\\ &= (3b/h^2)\times\delta\\ &= (3b/h^2)/(4\pi^2)(A_{sg}/F_s^{\,2})\times\alpha_b\\ &= (3b/h^2)/(4\pi^2)(A_s/F_s^{\,2})\times\alpha_s\end{aligned}$$

where, F_s is predominant frequency in Hz,
A_{sg} is combined amplification of ground and viaduct at predominant frequency F_{sg} in Hz.
F_{sg}, A_{sg}, F_s and A_s are derived from spectral ratio and QTS of microtremor.
Assuming the efficiency of dynamic load is e of static load for the effective strain ε_e,

$$\varepsilon_e = e\times(3b/h^2)/(4\pi^2)\times(A_{sg}/F_s^{\,2})\times\alpha_b = K_{sg}(e)\times\alpha_b \qquad (7)$$
$$= e\times(3b/h^2)/(4\pi^2)\times(A_s/F_s^{\,2})\times\alpha_s = K_s\,(e)\times\alpha_s \qquad (8)$$
$$K_{sg}(e) = e\times(3b/h^2)/(4\pi^2)\times(A_{sg}/F_s^{\,2})$$
$$K_s\,(e) = e\times(3b/h^2)/(4\pi^2)\times(A_s/F_s^{\,2})$$

where, K_{sg} for combined ground and viaduct and K_s for viaduct itself, are defined as above and it will be extended K_{sg} and K_s for 2-stories viaduct becomes as follow.

$$K_{sg}(e) = (75e/\pi^2)(A_{sg}/F_s^{\,2})(b\times h_i/(h_1^{\,3}+h_2^{\,3})), \qquad (9)$$
$$K_s(e) = (75e/\pi^2)(A_s/F_s^{\,2})(b\times h_i/(h_1^{\,3}+h_2^{\,3})), \qquad (10)$$

where b is width in vibrational direction of column, h_i is height of i-th column and $75/\pi^2$ is a coefficients selected so as calculated result to be in 10^{-6} unit, taking structural size in m, seismic acceleration in Gal and efficiency in %.

The formula shows K_{sg} or K_s of higher column layer is bigger for 2-storied viaduct which suggests more vulnerable to earthquake disaster. It corresponds well to the fact observed in case of Hyogo-Ken-Nanbu Earthquake that 2-storied viaducts with higher columns received much bigger damage.

Figure 5 shows K_{sg}-values of viaducts measured at every 100m along Shinkansen before the 1995 Hyogo-Ken-Nanbu Earthquake compared to the damage of viaducts. Here e = 100% is assumed. The figure indicates that collapsed viaducts correspond to K_{sg} peak values fluctuating in the range of $K_{sg} > 50$. K_{sg} values measured in advance well correspond to actual damage received. Thus K_{sg} values obtained before the earthquake are expected to predict the future earthquake damage precisely.

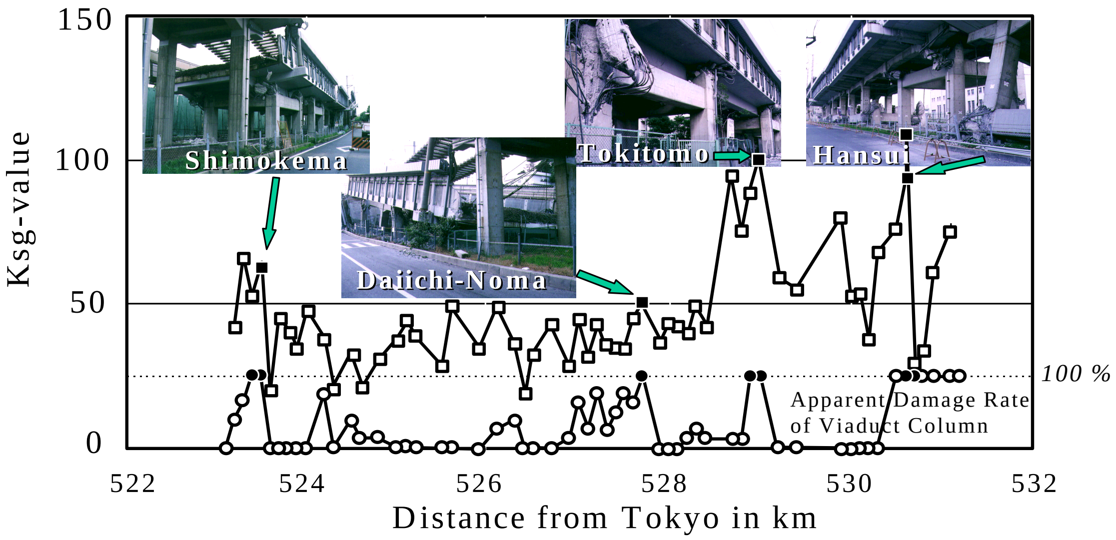

Fig. 5 Comparison between Viaduct Damage and K_{sg}-values measured before the Earthquake

d) Derailment/Overturn of Trains

To study derailment/overturn of trains work done per unit time (work rate) applied by earthquake motions is considered. Work rate w is proportional to the product of response acceleration $A\times\alpha_b$ and response velocity $A\times v$. As $v = \alpha_b/(2\pi F)$,

$$w = m\times A\times\alpha_b\times A\times v = (m/(2\pi))\times(A^2/F)\times\alpha_b^2 = (m/(2\pi))\times K_d\times\alpha_b^2, \quad (11)$$

$$K_d = A^2/F \quad (12)$$

where m is mass of objects receiving seismic force for instance trains or stone. It may possible to adopt K_d-value not only for train derailment/overturn but also structure damage or jumping stone by strong motion.

F and A are directly related to the seismic motion applied to the train body. The dynamic characteristics of trains are known in general, F and A can be estimated from F_g and A_g when a train stays on the ground surface, or from F_{sg} and A_{sg} of both structures and ground when a train stays on the structure.

Site characteristics is reflected in K_d-value. In case of large K_d-value, work rate w and possibility of derailment/overturn are also large. Thus K_d-value is considered as an index to indicate the vulnerability on derailment/overturn of trains.

Figure 6 shows derailment/overturn of stopping electric vehicles staying in the JR-Takatori yard due to the 1995 Hyogo-Ken-Nanbu Earthquake. Severe derailments occur approximately on the points with bigger K_d-values.

Figure 7 indicates derailments of running trains in time of the 1995 Hyogo-Ken-Nanbu Earthquake and K_d-values near the derailment sites every 20m approximately. It shows that whether trains derailed or not closely depends on K_d-values of the sites where trains were running.

Concluding Remarks

Vulnerability indices (K-values) of ground and structures due to earthquake motions have been proposed. K-values can be calculated from microtremors measured easily everywhere and it is not impossible to estimate the vulnerabilities of all structures and ground concerned.

In the near future, the data of K-values will be accumulated and the plan to do vibration rupture experiment to estimate damage degrees precisely from K-values and to examine validity of K-values as vulnerability indices will be done.

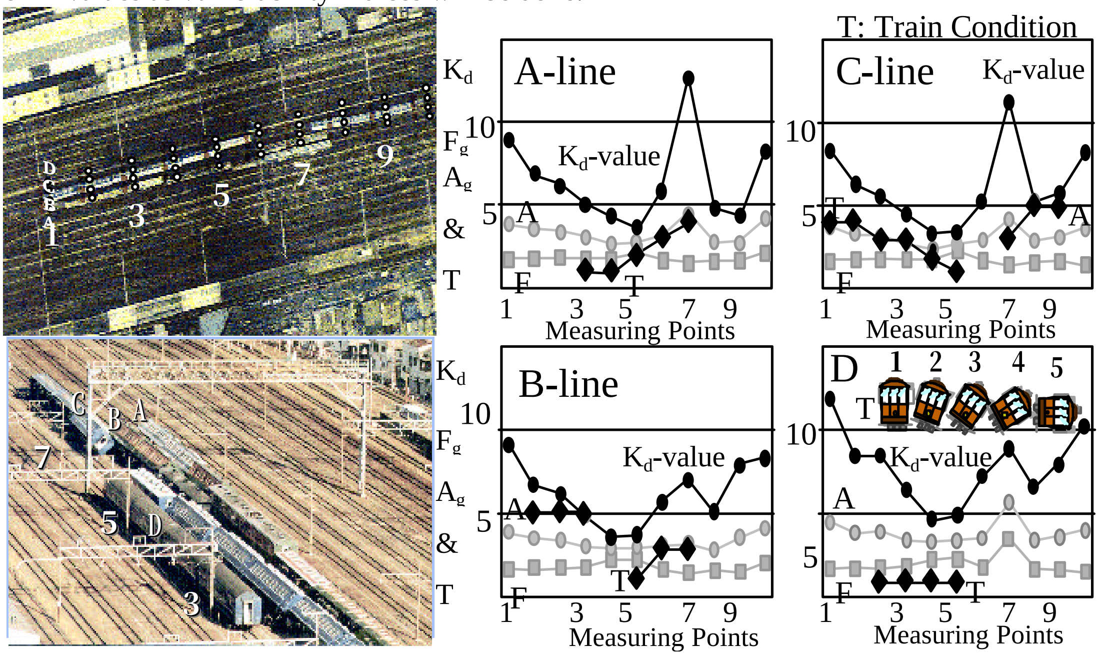

Fig.6 Relationship between Microtremor and Derailment/Overturn in JR-Takatori Yard

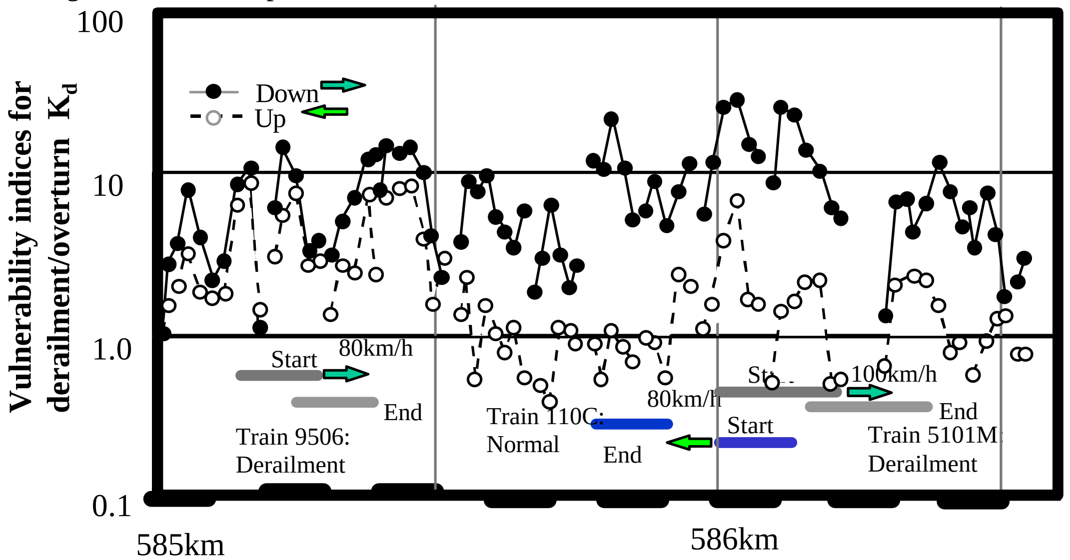

Fig.7 Relationship between K_d Distribution and Actual Situation of Trains along Railway

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