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REAL-TIME INFORMATION SYSTEMS FOR HAZARDS MITIGATION

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ABSTRACT

Constructing strong structures and facilities is an essential countermeasure in Earthquake Disaster Prevention (EDP). For railway system, the safety of passengers against strong motion are strongly concerned with running safety and stability of trains. The EDP, in general, required not only the hardware measures but also the software measures to minimize the influence of earthquake damage. In this paper the basic concept of the EDP are described and the real-time earthquake information systems, UrEDAS and HERAS, are outlined. Furthermore, as the element techniques of these systems, investigation methods and vulnerability indexes K values of ground and structures are proposed.

KEYWORDS

Earthquake warning system, UrEDAS, quick-response system, HERAS, micro-tremor, PIC, spectral ratio, QTS, vulnerability index, K-value

BASIC CONCEPT OF EARTHQUAKE DISASTER PREVENTION

Earthquake disaster countermeasures are based in principle to know both characteristics of earthquake motions and resisting power of structures against the earthquake motions. Earthquake damage occurs when earthquake power exceeds the resisting power or durability of the structures, including natural ones such as slopes. Disaster can be prevented provided we find weak points of structures beforehand and execute effective countermeasures in advance. Thus, it is really important to assume a few kinds of earthquakes which may attack the area and to clarify the weak points of structures by estimating the expected earthquake damage. However, practically it is impossible to reinforce the all estimated weak points before the earthquake.

Thus, following two points become indispensable for the earthquake disaster prevention, namely

(1) to estimate the present anti-seismic durability of existing structures, and
(2) to prepare always back-up countermeasures to avoid unexpected hazardous situation.

The latter item is a co-seismic countermeasure and it asks real-time response. For the former item, it is necessary to grasp the change of durability degree in time by measuring it with appropriate intervals.

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CONTINUOUS MONITORING EARTHQUAKE OCCURRENCE

Alarm Seismometer

Since second half of 1950s simple alarm seismometers have been installed along the railway in Japan by the then Japanese National Railways. Along the Tokaido Shinkansen, which started its operation in October 1964, same alarm seismometers were also installed. A local earthquake (M6.1) near Shizuoka in April 1965, urged to prepare an automatic train stop system using more reliable alarm seismometers. However, though the newly adopted alarm seismometer issues alarm when seismic acceleration exceeds a pre-set threshold, it could not give the final maximum acceleration experienced. When Tohoku Shinkansen was opened in 1982, the alarm seismometer was developed to set several alarm acceleration levels and indicate the maximum acceleration value with print-out as well as to give analog wave-form records. Since then similar alarm seismometers have been introduced for the conventional JR lines and other Shinkansens and now its number is more than four hundreds. The alarm seismometers are at present installed every 40~50 km along the conventional lines of JR, Japan Railways, and every about 20 km along the Shinkansens.

The alarm seismometer is installed on the ground surface and alarm is issued when horizontal acceleration exceeds about 40 Gal. The alarm is issued generally after S-wave arrives. If we set the threshold level lower, the seismic motion can be detected earlier. However, it easily responds to many environmental noise due to human activities such as traffic vibrations and industries and increases false alarms. Conventional alarm seismometer includes two following problems,
(1) alarm is too late to give enough time useful for the countermeasures, and
(2) frequent false alarm is issued for the harmless small earthquakes.
Above problems are based on the basic idea to issue an alarm, when seismic motion exceeds the pre-set threshold level. Thus, the problems can not be solved even when we use other quantities than the acceleration.

Earthquake Early Warning

In order to realize the early detection of earthquake, two following methods will be discussed,
(1) to detect earthquake in the epicentral area, which is named as "Front alarm",
(2) to detect earthquake by initial P wave, which is named as "P wave alarm".

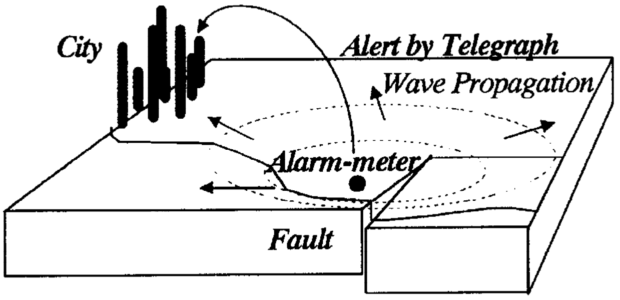

Fig. 1 Concept of the Front Alarm by Dr. Cooper

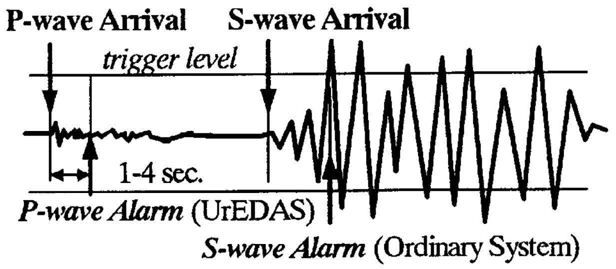

Fig. 2 The Timing of Alarms

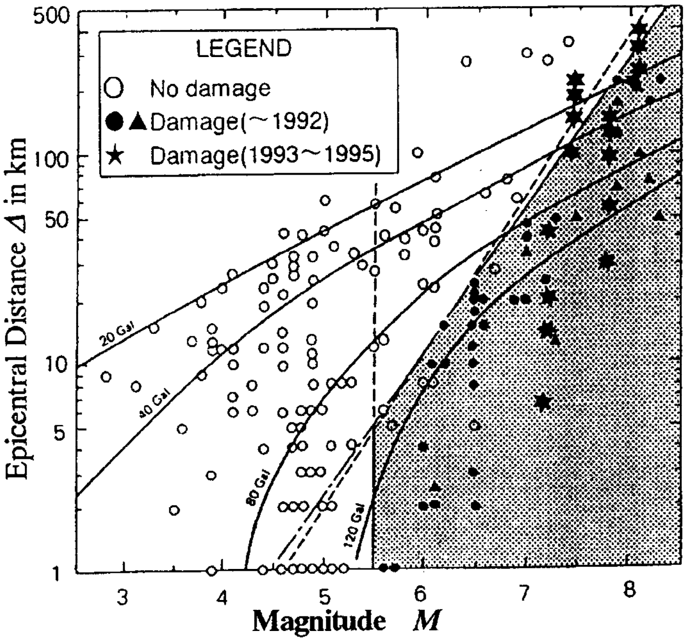

Fig. 3 Earthquake Damage on *M*-*Δ* plane

Front Alarm The idea of front alarm is explained in Fig. 1. The earthquake motions are detected as early as possible near the source to prepare against the earthquake before seismic motion reaches the site, using the difference of transmission velocities, electric communication (=300,000 km/s) and seismic wave (~8 km/s). This idea was first published in San Francisco Daily Evening Bulletin, 3. Nov. 1868, by J.D.Cooper, MD in San Francisco. He described the necessity of automation of the early warning system and problem of false alarm as well as the importance of public education for the warning. However, the then technical level could not realize his idea in practice.

After about 100 years, in 1972, Dr. Motohiko Hakuno (the then professor of Earthquake Research Institute, Univ. of Tokyo) and others proposed the same idea of Dr. J. D. Cooper for Tokyo instead of San Francisco. The then Japanese National Railways paid strong interest in this concept as a new installation to prepare against unexpected situations of railways due to strong earthquakes and promoted the research and development for this project. Thus JNR completed the Coast-line Detection System for the Tohoku Shinkansen (Nakamura *et al.*, 1982). And a Mexico City Seismic Alert System almost same as the Coast-line Detection System was insitalled in 1991 (Espinosa-Aranda, *et al.*,1995).

P-wave Alarm Fig. 2 shows seismic motion schematically. Conventional alarm seismometers detect earthquake motion when the main motion arrives(S-wave alarm). Alarm can be issued earlier if we defect the earthquake by P-wave. However P-wave alarm can not be done by issuing alarm merely when the earthquake motion exceeds certain pre-set threshold. If threshold level is lowered, detection can be done earlier, but false alarm occurs very often.

In order to examine new alarm method, past cases of earthquake railway damage are plotted in a diagram, taking earthquake magnitude in horizontal axis and epicentral distance in vertical axis as in Fig. 3. It clearly shows damage occurs M>5.5 and damaged areas are confined within certain distance range around the epicenter, For example, earthquakes with M6, M7 and M8 give damage within epicentral distances 12 km, 60 km and 300 km respectively. If we could estimate the earthquake magnitude and epicenter location with depth rapidly, the area to be alarmed is clearly shown by M-Δ diagram in Fig. 3 and reasonable alarm can be issued immediately after the earthquake.

DEVELOPMENT AND PRACTICAL USE OF UrEDAS

UrEDAS, Urgent Earthquake Detection and Alarm System, is a unique practical system and it first realized the real-time earthquake disaster prevention system in the world. The special feature of the system is the rapid alarm using information from P-wave data. It issues the alarm not simply because the seismic motion is strong, rather it issues the alarm for the area of sustain damage using the magnitude and hypocenter data obtained by P-wave observation.

In 1983 a prototype system using a personal computer which realized the basic function of UrEDAS was completed and since 1984 its test observations were executed in Miyako, Pacific coast city of Tohoku District, and other places. Then an UrEDAS network for the Tokyo Metropolitan Area consisting five UrEDAS was established in 1988-1989 by the subsidy of the Ministry of Transportation. In March 1988 four UrEDAS was also installed for the Seikan Under-Sea Tunnel between Honshu and Hokkaido as a part of its earthquake disaster prevention system. For the Tokaido UrEDAS at Omaezaki, Shizuoka Prefecture, started limited use in September, 1990 and in March 1992 fourteen UrEDAS surrounding the Tokaido Shinkansen line was installed to put in practice the P-wave alarm functions. Since 1992 earthquake hypocenter information with map, obtained by the Metropolitan UrEDAS, has been delivered by FAX to about 50 limited test users as real-time service about 4 minutes after each earthquake.

In September 1992 an UrEDAS was installed in Kresge Seismological Laboratory, California Institute of Technology (Caltech), Pasadena, California, USA as a joint research project of RTRI with Prof. H. Kanamori of Caltech. This Pasadena UrEDAS observed the Northridge Earthquake, 17 January 1994, and its aftershocks.

UrEDAS gives location, depth and magnitude of the earthquakes in order to estimate the impending damage promptly. To know these earthquake dimension, data at many observation points are usually used. However, considering the

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complexity of multi-station system and weakness of network system, UrEDAS adopted single station for the alarming. By monitoring the earthquake motions of a single observation point in real-time, an UrEDAS detects initial P-wave motion, estimates epicenter azimuth and magnitude, calculates epicentral distance and focal depth as the first inference within about 3 seconds after detecting P wave. This is the actual function of UrEDAS practically in use for Tokaido Shinkansen since March 1992. With respect to the locations of epicenter and UrEDAS point, the alarm eventually reaches target area before the P-wave arrival. UrEDAS issues the first alarm information 1-4 sec just after P-wave arrival and sends out the second information after arrival of S-wave.

Even in case of using plural UrEDAS, individual UrEDAS estimates the earthquake elements separately and sends necessary alarm by individual judgment. Information of earthquake elements decided by each individual UrEDAS is collected in the UrEDAS center and synthesized into final earthquake elements with higher accuracy. For example Center System of Tokaido UrEDAS automatically output a Re-Operation Procedure Recommendation Sheet of countermeasures for the alarmed earthquake within two minutes after P-wave arrived at the first UrEDAS station.

Ordinary centralized alarm system looses its total function when its center equipment are once destroyed. On the contrary, UrEDAS is a completely autonomous and dispersed system, and even for a destructive earthquake its system function is never out of function simultaneously. Even when main earthquake motions destroy an UrEDAS, it has already issued the alarm and necessary information has been already communicated to the necessary areas.

In addition, UrEDAS responds to big earthquakes far from the railroads, while conventional alarm seismometers function against local strong earthquakes just beneath the line and both systems compensate their roles each other. At present, in December 1995, we have twenty five sets of UrEDAS in Japan (see Fig. 4) and one set in USA. In 1996 five sets of UrEDAS will be established for the San'yo Shinkansen and many new installation is also under planning.

Examples of Earthquake Monitoring by UrEDAS

The principle of UrEDAS was reported at the 9th WCEE. Here we present how UrEDAS functioned in times of Northridge Earthquake, 17 January 1994, and Hyogo-Ken-Nanbu Earthquake, 17 January 1995.

During the first 24 hours after the Northridge Earthquake, UrEDAS detected about 700 aftershocks of which their magnitudes and hypocenters were automatically determined as shown in Fig. 5. All earthquakes detected by the Pasadena UrEDAS were indicated graphically on the office room of Seismological Laboratory of Caltech immediately after each event. In addtion the Psadena UrEDAS information was sent to CUBE and referred as useful data.

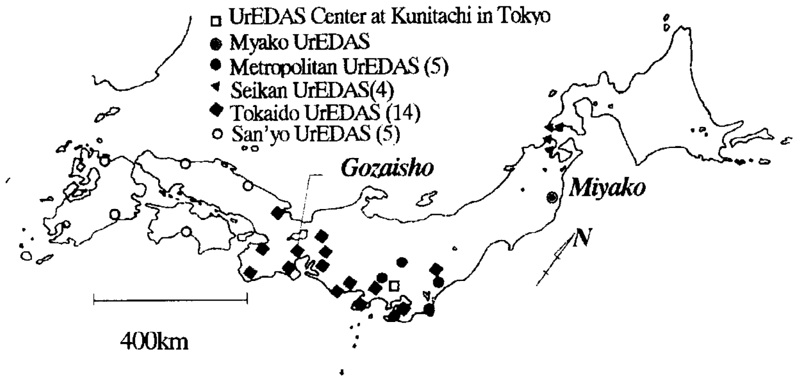

Fig. 4 Distribution of UrEDAS in Japan

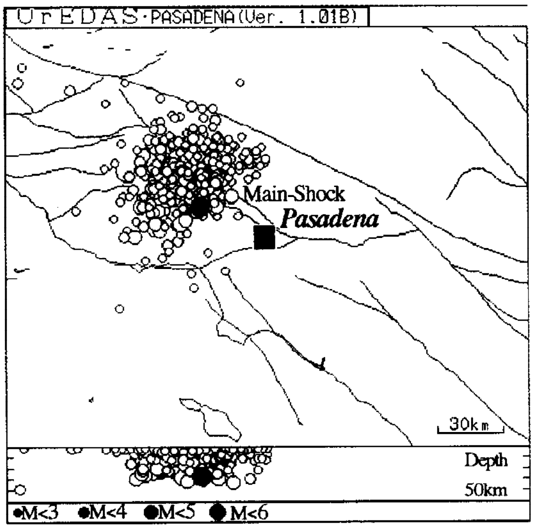

Fig. 5 The Northridge Earthquake Sequence by Pasadena UrEDAS

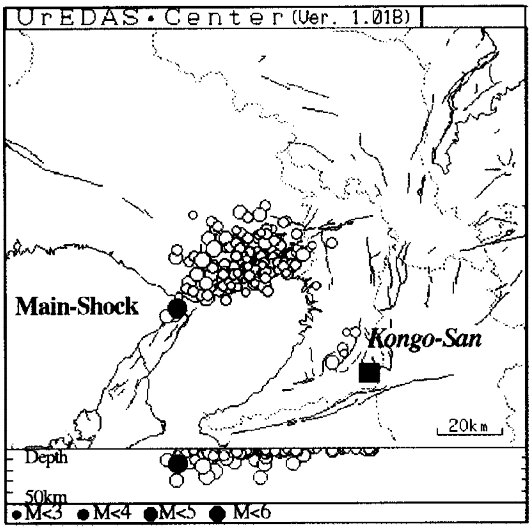

Fig. 6 The Hyogo-Ken-Nanbu Earthquake Sequence by Kongo-San UrEDAS

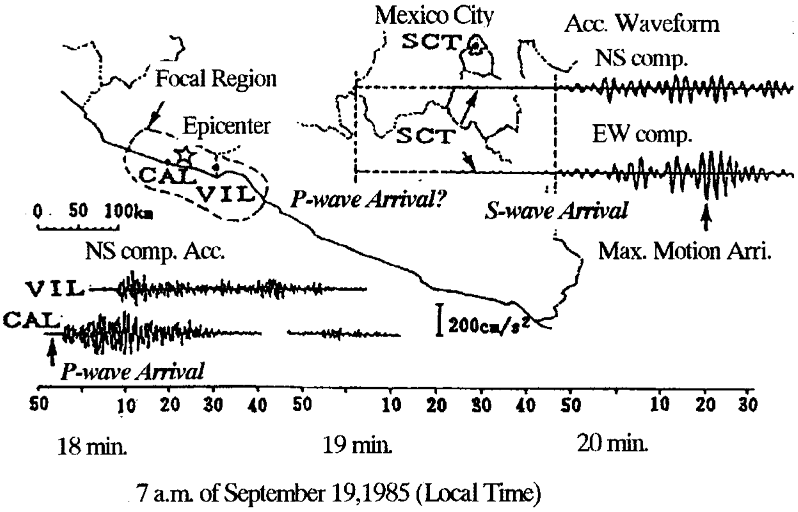

Fig. 7 Strong Motion Propagation at the 1985 Michoacan Earthquake

Fig. 6 shows the monitor result by Kongo-San UrEDAS for the Hyogo-Ken-Nanbu Earthquake sequence before 30 Jan. 1995. Although it used data at single station, aftershock activity was almost correctly traced. The Hyogo-Ken-Nanbu Earthquake, for the Shinkansen, occurred just beneath the line and alarm seismometers along the line have responded the event. The recorded seismograms showed that strong seismic motions arrived successively at the alarm seismometers installed every 20 km along the line and each seismometer issued alarm within a few seconds one by one. All Tokaido UrEDAS, except one at Gozaisho, judged the Hyogo-Ken-Nanbu Earthquake as harmless for Tokaido Shinkansen and did not issue the alarm. But alarms from the seismometers along the line reach almost simultaneously the alarm from UrEDAS nearest to the line, which showed that the alarm seismometer along the line functioned as expected.

Time Margin and its Effect for Disaster Prevention

Fig. 7 shows that, if UrEDAS installed along the Pacific coast of Mexico issues alarm, P-wave of the 1985 Michoacan Earthquake reaches Mexico City one minute after the alarm and main strong motions causing damage arrives there another one minute later. Namely there is two minutes margin time for Mexico City, and even if UrEDAS is installed only in Mexico City, still there is one minute margin. This margine time expected by UrEDAS in Mexico City is nealy equal to that of the Mexico City Seismic Alert System consists of seismometers along the Pacific coast of Mexico. Adequate refuge reaction, use of anti-shelter in high rise building floor, etc. can be recommended to use the margin time.

UrEDAS gives prompt first alarm within a few seconds and provides more exact information about one minute after it detects the event. It is not only useful for the safeguard of train and automobile transportation, but also expected to be applied widely for the different disaster prevention problems as follow: trigger of active control devices of building, control of elevator of high-rise building, earthquake countermeasures of chemical plant and nuclear power plant, tsunami warning for the harbor and coastal publics, early response of fire-fighting, preparedness of hospitals etc.

DURABILITY OF GROUND AND STRUCTURES (ESTIMATION OF DAMAGE)

Beside monitoring of earthquake forces, another basis for the earthquake disaster prevention is to know exactly the durability of ground and structures. It is important to grasp "present" durability correctly. Earthquake damage depends upon strength, period and duration of seismic motions. Besides nature of earthquake itself, these parameters reflect strongly seismic response of surface ground and structures. Thus the vulnerable weak points can be easily disclosed by examining seismic motion characteristics of surface ground and structures.

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Estimation of Seismic Characteristics of Surface Ground and Structures

Characteristics of seismic motions of surface ground effective to earthquake damage can be approximately evaluated by boring investigations. However, the investigations needs a many time and cost which hinders it at many places.

Noting the relation between horizontal and vertical earthquake motions obtained by strong motion seismometer (Nakamura *et al.*, 1983), seismic characteristics of surface ground will be approximated with the spectral ratio of horizontal to vertical components of ground surface microtremors (Nakamura, 1989). Here we name this spectral ratio as QTS (Quasi-Transfer Spectrum). Natural frequency F and amplification factor A of surface ground can be correctly measured from QTS of microtremors of surface ground. This fact has been recognized by many researches with numerical experiments or field observations (for example, Lermo *et al.*, 1993).

Seismic response characteristics of structures can be estimated from spectral ratio of microtremors observed simultaneously on the structures and on the ground surface near the structures. QTS of microtremors on the structure represent the combined characteristics of surface ground and the structure.

Fig. 8 shows results of microtremor observations executed every 100m along certain railway line. HERAS, Hazards Estimation and Restoration Aid System, which will be described later, includes these results as data base. QTS of the structure and surface ground may be calculated by microtremors. Fig. 8 shows clearly that the form of QTS of surface ground corresponds very well to the geologic and topographic structures.

Until now microtremors have been measured at more than 20,000 sites mainly along the railroads every 100 m. In order to make possible such large number of microtremor measurement, PIC, Portable Intelligent Collector, was developed in 1986. Since 1986, three types of PIC, PIC86, PIC87 and PIC91, had been developed.

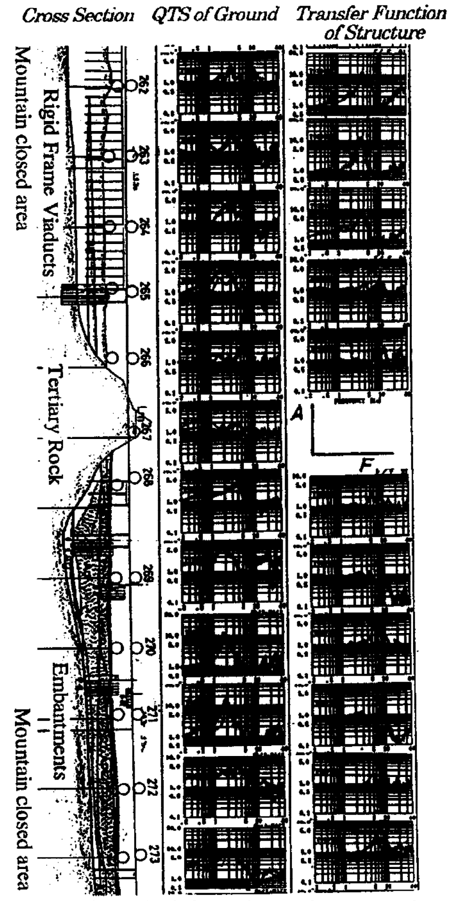

Fig. 8 Basic Administration Diagram of Earthquake Disaster Prevention for Railways

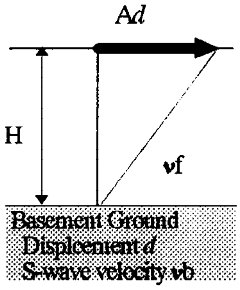

Fig.9 Deformation of Surface Layer

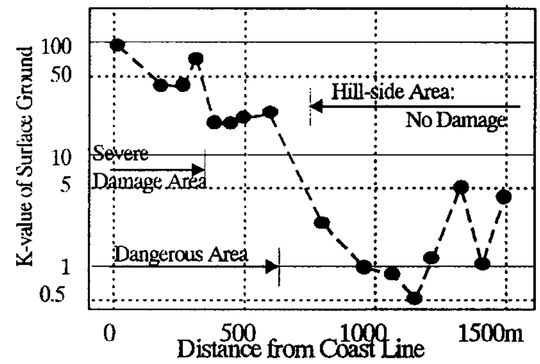

Fig. 10 K-values in SF Marina District

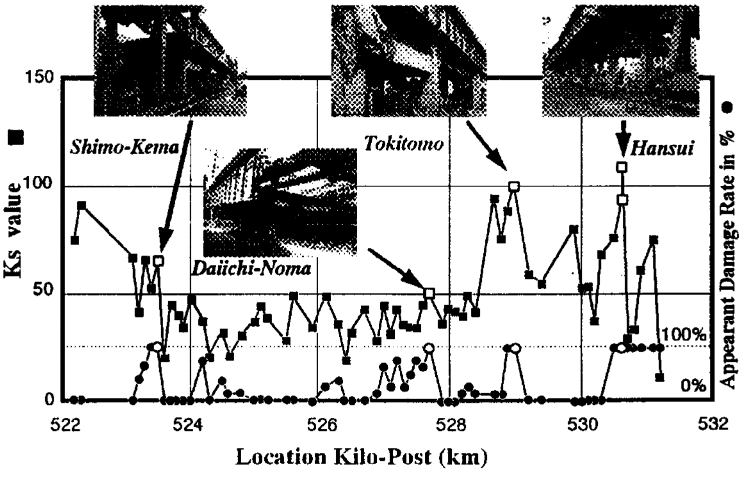

Fig. 11 Comparison the Damage and Ks values of the Rigid Frame Viaduct of San'yo Shinkansen

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Vulnerability Indexes K-values of Ground and Structures

K-values have been proposed, in order to estimate the earthquake damage of ground and structures accurately.

K-value of Surface Ground For the vulnerability index K of surface ground, shear strain γ is considered. Table-1 shows relationship between damage of foundation and size of γ (Ishihara, 1982). According to this table, ground soil becomes to plastic state at about $\gamma = 1000\text{x}10^{-6}$ and for $\gamma > 10000\text{x}10^{-6}$ landslide or collapse of foundation occurs.

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, Diff. Settlement		Landslide, Soil Compaction, Liquefaction	
Dynamic Properties	Elasticity		Elasto-Plasticity	Repeat- Effect, Speed- Effect of Loading		

Simplifying the shear deformation of surface ground as shown in Fig. 9, average shear strain γ can be estimated as $\gamma = Ad/H$, where A is amplification factor of surface layer, H is thickness of surface layer and d is seismic displacement of the basement. Putting the S-wave velocities of the basement and surface layer are v_b and v_f respectively, natural frequency F of the surface layer can be expressed as $F = v_b/(4HA)$. Acceleration a in the basement is able to express $a = (2\pi F)^2 d$, then shear strain γ is expressed as follow.

$$\gamma = (Aa/(2\pi F)^2)(4AF/v_b) = (A^2F)(a/\pi^2 v_b) = \alpha K a$$

where $\alpha = 1/(\pi^2 v_b)$, $K = A^2F$. α is expected almost constant for various sites. K-value is an unique value correspond to the site and can be considered as a vulnerability index of the site, which is expected useful to select weak points of ground. Putting $v_b = 600\text{m/s}$ (Nakamura *et al.*, 1990) α become to $\alpha = 1.69\text{x}10^{-6}$ (s/cm). If effective strain is considered about 60% of estimated maximum strain, effective strain can be estimated by K-value multiplied with maximum basement acceleration in Gal.

Fig. 10 indicates K-values at SF Marina obtained by microtremor measurements in San Francisco Bay Area after the 1989 Loma Prieta Earthquake. According to this, the sites K>20 liquefied, while K-values in the area with no damage were much smaller. Considering the maximum accelerations near the sites, surface ground liquefied in $\gamma > 1000\text{x}10^{-6}$.

K-value of Column of Rigid Frame Viaduct Concrete columns are designed in general to be collapsed by bending moment. Vulnerability index Ks for column of rigid frame viaduct is derived from marginal strain ε due to the bending moment at upper and lower ends of column. Namely, marginal strain ε of the upper and lower column ends are obtained by multiplying Ks with maximum acceleration of basement layer. Ks value for i-th story column of the two-storied rigid frame viaduct is defined as follow (Nakamura *et al.*, 1994, Sato *et al.*, 1995).

$$Ks = (7500/\pi^2)(Asg/F^2)\text{X}(b\, h_i/(h_1^3+h_2^3))$$

where Asg is combined amplification factor of surface ground and the viaduct itself, F (in Hz) is first order natural frequency of the viaduct, b (in m) is width of the column in vibrating direction and h_i (in m) is column height of i-th story. In addition $7500/\pi^2$ is a coefficient to adjust the calculated result be in unit 10^{-6} strain, when seismic acceleration is measured in unit Gal (cm/s^2). The formula indicates larger Ks for the higher column of two-storied rigid frame viaduct which receive damage more. This corresponds the actual viaduct damage in the Hyogo-Ken-Nanbu Earthquake.

Fig. 11 shows damage of Hyogo-Ken-Nanbu Earthquake, with Ks values calculated from the microtremor data of surface grounds and rigid frame viaducts along the Shinkansen measured at every 100m intervals before the Earthquake. The result indicates that the collapsed viaducts are found where (1) Ks>50 and (2) Ks values show peaks. Ks measured before the Earthquake correspond very well to the damage actually happened by the Earthquake. Thus, we can conclude that earthquake damage will be predicted correctly by using Ks values obtained before the earthquakes occur.

ESTABLISHMENT OF HERAS

HERAS, Hazards Estimation and Restoration Aid System, is a system which estimates detailed earthquake damage situation promptly by receiving information from UrEDAS, and using investigation results of vibration characteristics of foundation grounds and structures obtained by microtremors (results of microzonation) as data base. By estimating the impending damage situation in detail HERAS helps rapid, reasonable restoration of railway operation. HERAS is able to show the estimated results in visual and in numerical tables within a few minutes after the earthquake. HERAS also can help reasonable routine maintenance and use its function in ordinary time.

As explained in the previous sections, vulnerability indexes K-values, defined for surface grounds, embankment , and structures such as rigid frame viaduct, are useful to estimate earthquake damage correctly. At present HERAS predicts and illustrates the damage by statistical methods within 5 minutes. A new HERAS which can give much more precise damage prediction using K-values, is being developed as a heart of the general disaster prevention system, which can be used for complex disaster combined, various natural disasters such as flood and earthquake.

CONCLUDING REMARKS

Natural disasters isolate every one from others and autonomous judgment and action of individual person becomes important. Disaster prevention system itself may be also isolated in time of disasters. Thus UrEDAS was planned as a system which can function autonomously and does not presume network operation without human interference. Of course, plural UrEDAS can work as a network to give synthetic information with higher accuracy to HERAS.

On the contrary for HERAS communication with human work is important, because HERAS is expected to help human action for the rapid, reasonable restoration works. The system may get out of order or discontinue to receive information and the operators who use the system should use information from the system critically and utilize it autonomously, checking it with information from other sources. The author hopes in future to develop disaster prevention systems such as UrEDAS and HERAS helping autonomous human actions for the disaster prevention.

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