ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 10, NO. 5 (2009)
PAGES **-**

RESEARCH ON RELIABILITY ASSESSMENT OF BURIED TELECOMMUNICATION FACILITIES DURING EARTHQUAKES

M. Nakano[*a], S. Takada[b], T. Suzuki[c] and T. Takatani[d]
[a]Department of Civil Engineering, Osaka-Sangyo University, Japan,
[b]School of Civil Engineering, University of Tehran, Iran
[c]Department of Civil and Environmental Engineering, Faculty of Engineering, Toyo University, Japan
[d]Department of Civil Engineering, Maizuru National College of Technology, Japan

ABSTRACT

In past earthquakes, a lot of damage occurs to the city supply systems such as electricity, gas, drinking and sewer water, telecommunications as known in the 1983 Nihonkai Chubu earthquake, 1995 Hyogoken Nambu earthquake and 2004 Niigata Chuetsu earthquake. The seismic safety of the telecommunication facilities is extremely important among other lifelines for the disaster recovery in the emergency activities after earthquakes. Underground telecommunication facilities are composed of telecommunication cables and conduits accommodating cables. In the present study, the earthquake resistance evaluation technique of underground telecommunication facilities was examined by the probabilistic method, focusing on its earthquake safety.

Keywords: Earthquake; telecommunication facilities; non-linear analysis; reliability probability; ERAUL

1. INTRODUCTION

Malfunction of lifeline systems by physical damage during recent earthquakes gave great impact to citizen's daily life. Serious loss of human-life and properties were caused due to lifeline malfunction especially in densely populated urban areas.

Various researches on lifeline performance and evaluation of lifeline function have been done so far in the field of earthquake engineering. Seismic safety of telecommunication system is extremely important for emergency response and restoration works among various lifelines. However, the research on the seismic safety of telecommunication systems has not been done so much. The research on the evaluation of seismic safety of telecommunication systems is indispensable for the urban disaster mitigation plan.

Telecommunication cables are accommodated in buried structures such as pipelines and /or

*Email address of the corresponding author: nakano@ce.osaka-sandai.ac.jp (M. Nakano)

conduits. Then the physical damage to the buried structures does not mean the malfunction of telecommunication systems, though the damage of gas or water pipelines caused the stop of supply. The relation between damage of buried structures and cable function is important for the seismic evaluation of the buried telecommunication facilities [1].

Present paper aims to make clear the seismic safety of buried telecommunication facilities under consideration of the coupling behavior of the buried structures and cables.

First, the structural features are investigated for the buried structures involving buried pipeline, conduit and cable.

Second, seismic hazards of wave propagation, ground subsidence in soft ground and ground settlement and lateral flow by liquefaction are treated as seismic inputs to the buried structures of the telecommunication systems.

Third, probability of the seismic reliability of buried structures is theoretically obtained by comparing response values with allowable ones by employing computational models under above seismic inputs. Finally, the damage probability of telecommunication cables is experimentally obtained by the use of relation between damage of the buried structures and deformation of the cables. Moreover, a computer program on the probabilistic seismic evaluation method for the buried telecommunication facilities would become possible [2].

2. OUTLINE OF TELECOMMUNICATION BURIED STRUCTURES

In the present chapter, buried pipeline, cable tunnel and cable of the buried telecommunication structures are outlined as follows [3].

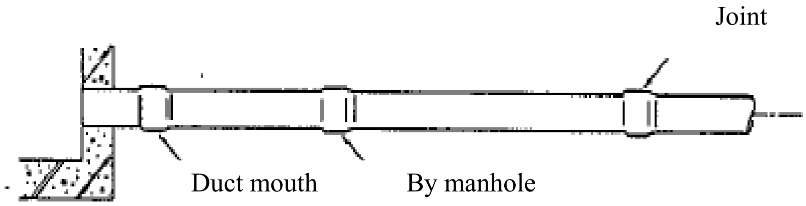


Fig.1 Pipeline part connected to structure

2.1 Buried pipeline

The buried pipelines are divided into straight pipes and connected pipes to structures (Fig. 1). There exist 11 and 16 kinds of the combination of pipe body and joint in the straight pipe and connected pipe respectively. 90% of pipes is steel pipe with jute (SA), coated steel pipe (PS), ductile iron pipe(Id) and polyvinyl pipe(V). The remains are concrete pipe(C) and asbestos pipe (AP).

Damage of the buried pipes was occurred at the sites of liquefaction areas, ground settlement and fissure areas in soft and reclaimed ground, and permanent ground deformation areas behind bridge abutments. High rate of damage was observed in C and AP pipes which must be checked for their seismic safety reliability probability.

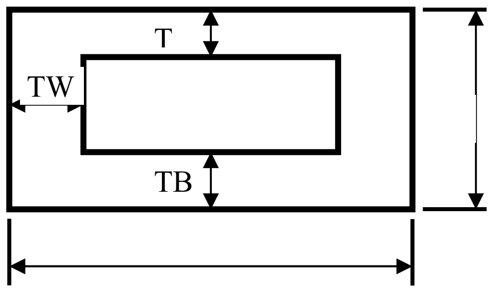
Telecommunication pipelines are buried in multi-step and multi-column which cause different performance of the pipes in upper and lower positions. Seismic safety reliability shall be obtained for different position pipes.

2.2 Cable tunnel

Telecommunication cable tunnel are classified into 2 construction methods of open cut and shield cable tunnel, 2 materials of reinforced concrete and steel materials and 3 parts of general straight, connected to structures and shaft parts.

Table 1. Cross section features of open cut cable tunnel (unit：m)

Type number	**TU**	**TB**	**TW**	**H**	**B**
No-1	0.250	0.300	0.250	2.800	2.550
No-2	0.250	0.300	0.250	2.800	2.950
No-3	0.250	0.350	0.350	4.050	3.150
No-4	0.250	0.400	0.400	4.200	4.800



There are different cross section features of open cut and shield cable tunnel. Cross section features of open-cut and shield tunnels are listed in Table 1 and 2. The cable tunnel has higher reliability due to their higher rigidity compared by buried pipes. Shield tunnel has highest reliability due to deep construction compared with open cut cable tunnel without any effects of liquefaction and ground settlement.

Table 2. Cross section features of shield cable tunnel (unit: m)

Material of segment	**Type number**	**Inner diameter**	**Outer diameter of segment**	**Segment pieces**
Steel segment	No-1	2.550	3.150	6
	No-2	2.950	3.550	7
	No-3	3.950	4.550	7
	No-4	4.400	5.100	7
Reinforced segment	No-1	2.550	3.250	5
	No-2	2.950	3.700	6
	No-3	3.950	4.750	6
	No-4	4.400	5.250	6

2.3 Cables

Fig. 2 shows failure modes of telecommunication cables. Following two modes are considered.

1) Damage of cables at parts of pipe body -break or pulling out at pipe joints.

2) Cable connecting parts in manholes are failed due to pull and push movement of cables by vibration failure of pipe joints.

Present paper will obtain the probability of seismic safety reliability of 5 types of cables (coaxial, optical fiber, PEC, STAL and lead coating cables).

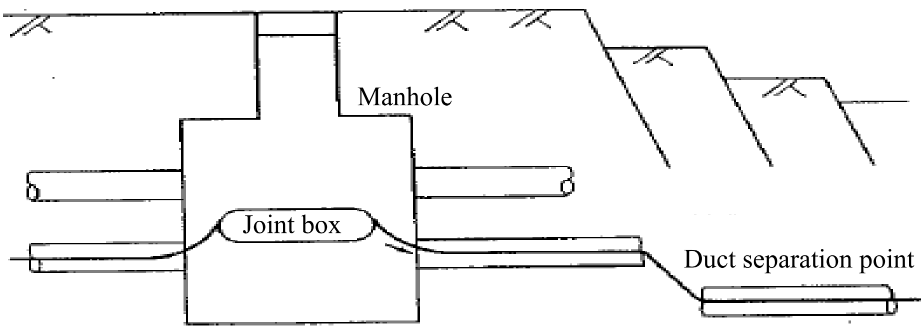


Fig. 2. Case of cable damage

3. PROBABILITY OF THE RELIABILITY OF PIPE AND CABLE TUNNEL

Present chapter shows the methodology to obtain the probability of the seismic safety reliability for pipe and cable tunnel. Fig. 3 shows analytical flow to obtain probability of the seismic safety reliability of telecommunication pipeline and cable tunnel. Straight part and connected part of the pipeline are analyzed for obtaining the reliable probability which can be calculated by comparing response and allowable values. Models are analyzed on straight, connected and shaft parts of the cable tunnel for standard sections of these facilities. Response values in other parts besides the standard sections are calculated by using conversion coefficients. Response values both for pipelines and cable tunnel are simulated by using ERAUL (Earthquake Response of Underground Lifelines) computer program which can consider non-linear behavior of pipe materials, joint characteristics and ground stiffness springs.

3.1 Seismic inputs

Following seismic inputs are set under consideration of damage in past earthquakes.

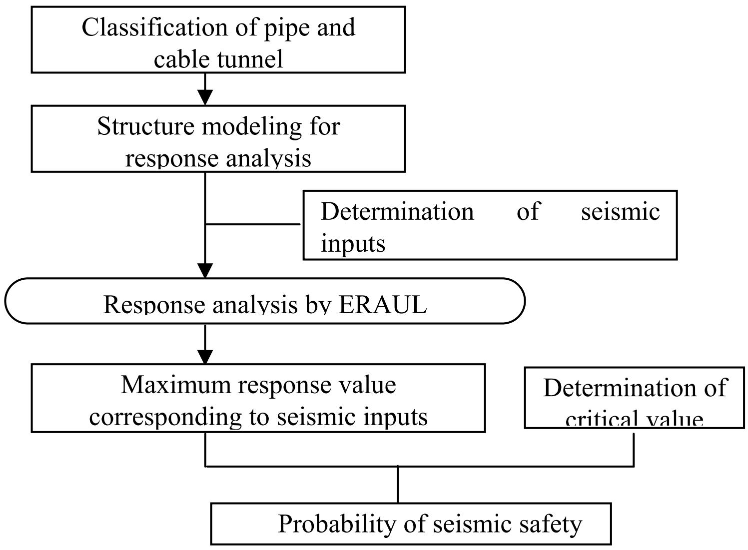


Fig. 3 Analytical flow for probability of seismic safety reliability of pipeline and cable tunnel

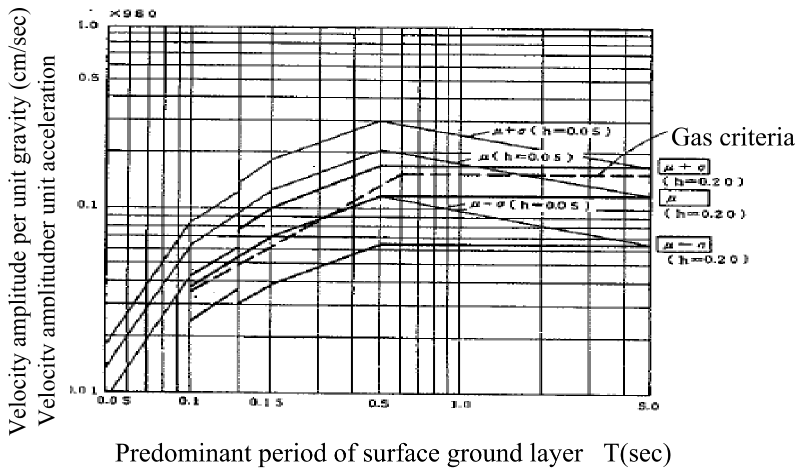


Fig. 4 Seismic design-velocity spectra

As for wave propagation inputs, deterministic seismic design-velocity spectra has been specified in the seismic design codes of petroleum, high pressure gas and common duct facilities in Japan[4-6]. However a probabilistic design spectra has been employed to obtain the probability of seismic safety for telecommunication facilities as shown in Fig.4. The proposed design spectra shows a little higher level in average than the spectra specified in gas design code and a little lower value in longer period which is considered to be an appropriate range [7].

Method to calculate wave length for ground strain is based on the petroleum code [4] which gives averaged wave length in bed rock and surface layer where the structures are buried. Table 3 shows S-wave velocity (*Vs*), predominant period (*T*) and wave length (*L*) depending on the soil classification. The ground strain obtained by the present methods shows a little higher value than those by the gas code, which gives the safety side,seismic inputs for the probability of the seismic reliability [8].

Table 3. S-wave velocity depending on the soil classification

Ground type	***Vsb* (m/sec)**	***Vs* (m/sec)**	***T* (sec)**	***L* (m)**
1	300	260	0.15	4.5
2	300	200	0.30	7.2
3	300	150	0.50	100
4	300	100	0.70	105

Table 4. Seismic inputs for wave propagation

Seismic intensity scale (JMA Scale)	Base seismic intensity *Koh*	Ground type	1		2		3		4	
			Tg ≤ 0.2		0.2<*Tg*≤ 0.4		0.4<*Tg*≤ 0.6		*Tg*>0.6 (s)	
		T (s)	0.15		0.30		0.50		0.70	
		C (m/s)	300		240		200		150	
		L (m)	45		72		100		105	
			Average (μ)		Average (μ)		Average (μ)		Average (μ)	
			μ-σ	μ+σ	μ-σ	μ+σ	μ-σ	μ+σ	μ-σ	μ+σ
		Sv (cm/s)	52		86		114		114	
			25	60	47	125	63	165	63	165
V (-)	0.075	*Uh* (cm)	0.12		0.39		0.57		1.21	
			0.08	0.15	0.21	0.57	0.48	1.25	0.57	1.76
		Strain $x10^{-4}$	1.65		3.42		5.44		7.26	
			1.11	2.20	1.57	4.97	2.00	7.88	4.01	10.50
V (+)	0.15	*Uh* (cm)	0.24		0.75		1.73		2.43	
			0.16	0.31	0.43	1.14	0.95	2.51	1.34	3.51
		Strain $x10^{-4}$	3.31		6.54		10.88		14.51	
			2.23	4.39	3.74	9.95	6.02	15.76	0.02	21.01
VI	0.20	*Uh* (cm)	0.32		1.05		2.31		3.23	
			0.21	0.42	0.57	1.52	1.27	3.34	1.79	4.55
		Strain $x\ 10^{-4}$	4.41		9.12		14.51		19.35	
			2.97	5.86	4.99	13.26	8.02	21.01	10.70	28.01
VII	0.30	*Uh* (cm)	0.47		1.57		3.47		4.65	
			0.32	0.03	0.86	2.28	1.91	5.02	2.68	7.02
		Strain $x\ 10^{-4}$	6.62		13.69		21.77		29.03	
			4.46	8.79	7.48	10.89	12.03	31.51	16.04	42.02

Uh= $\frac{2}{\pi^2}.T.Sv.Koh$

***Uh*: Ground response displacement (cm)**
***Sv*: Response velocity per unit seismic intensity (cm/sec)**
***T*: Predominant period (sec)**
***Koh*: Seismic intensity on basic ground**

Table 4 indicates ground response displacement and strain depending on seismic intensity and ground condition.

1) Permanent ground settlement displacement 0~50 cm is introduced as seismic inputs in soft, reclaimed, fill and behind grounds of bridge abutment.

2) Permanent fissure displacement 0~50 cm is introduced in soft and reclaimed grounds.

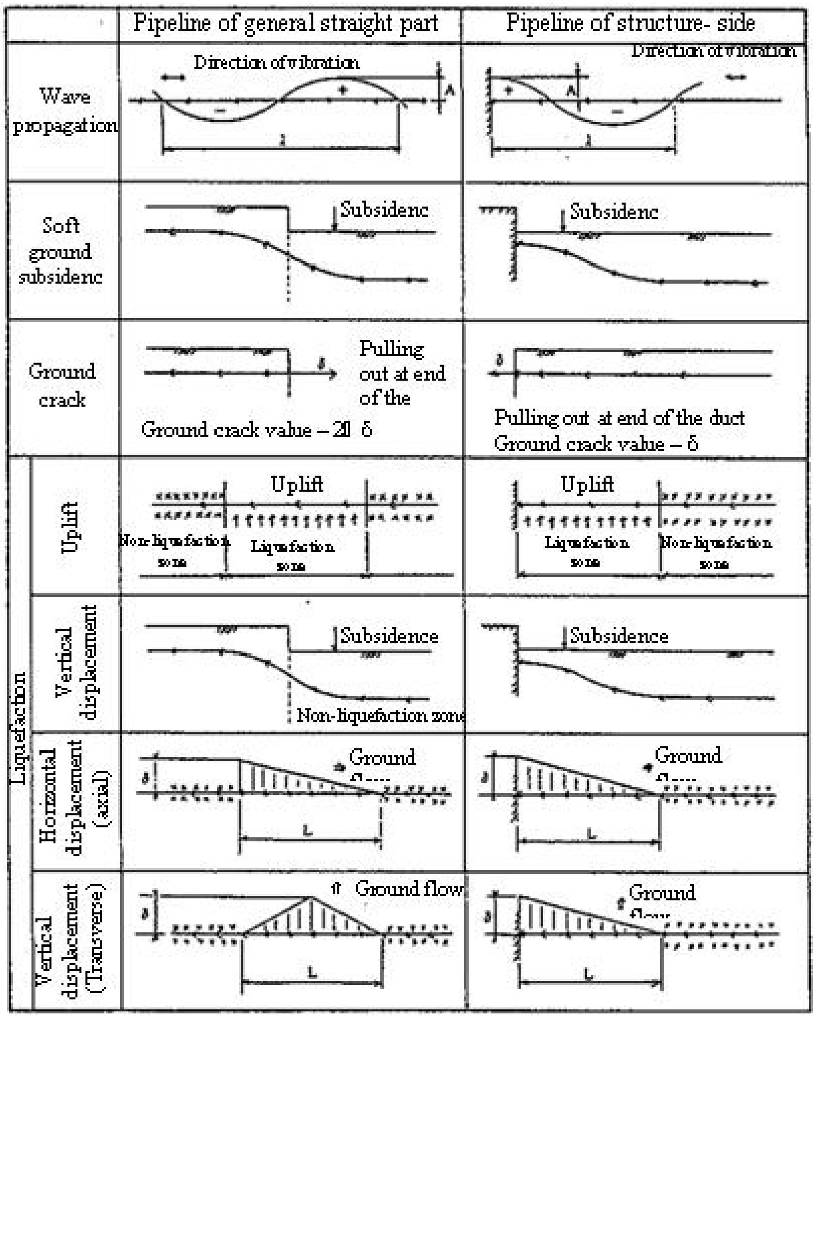
3) Permanent liquefaction force and displacement are considered for buoyancy, vertical, axial and transverse displacements. The area of the liquefaction is obtained for the case giving critical response and also based on past earthquake case studies.

3.2 Analytical model for each seismic input

3.2.1 Analytical model

Table 5 shows analytical models for cable tunnel under various seismic inputs. Ground models are same as that used for pipe models.

Table 5. Analytical models



3.2.2 Ground model

Fig. 5 and Table 6 show bi-linear spring for ground model which was obtained by experiments [9].

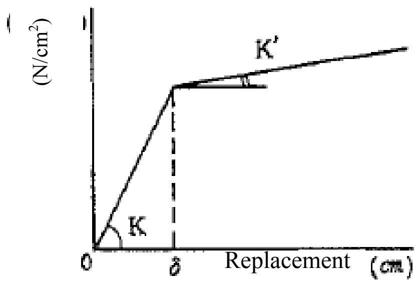


Fig. 5 Bi-linear model of ground

Table 6. Characteristic value of ground spring constants used for analyses

Ground spring Pipeline	**Axial (x10^{-1})**			**Transverse (x10^{-1})**		
	***K* (N/cm^3)**	***K* (N/cm^3)**	**δ (cm)**	***K* (N/cm^3)**	***K* (N/cm^3)**	**δ (cm)**
PS, SA	0.593	0.0514	0.50	0.272	0.00272	4.0
I, Id	1.184	0.0299	0.44	0.272	0.00272	4.0
V	0.272	0.0922	0.64	0.272	0.00272	4.0
C	0.683	0.0578	0.53	0.272	0.00272	4.0
AP	0.683	0.0578	0.53	0.272	0.00272	4.0

3.2.3 Pipe joint model

Joint spring characteristics of pulling, pushing and rotation are obtained by experiments. The joint characteristics for old pipes are estimated by using experimental results for re-produced pipes based on old drawings and also by consideration of joint mechanical characteristics. Table 7 is part of joint characteristics of coated steel pipe (PS). Table 8 shows expansion and contraction, and rotation of a ring bolt of the shield joint and also a water leakage-prevention joint of connected parts of the open cut tunnel to buildings [10-11].

Table 7. Joint characteristics (Example of coated steel pipe: PS)

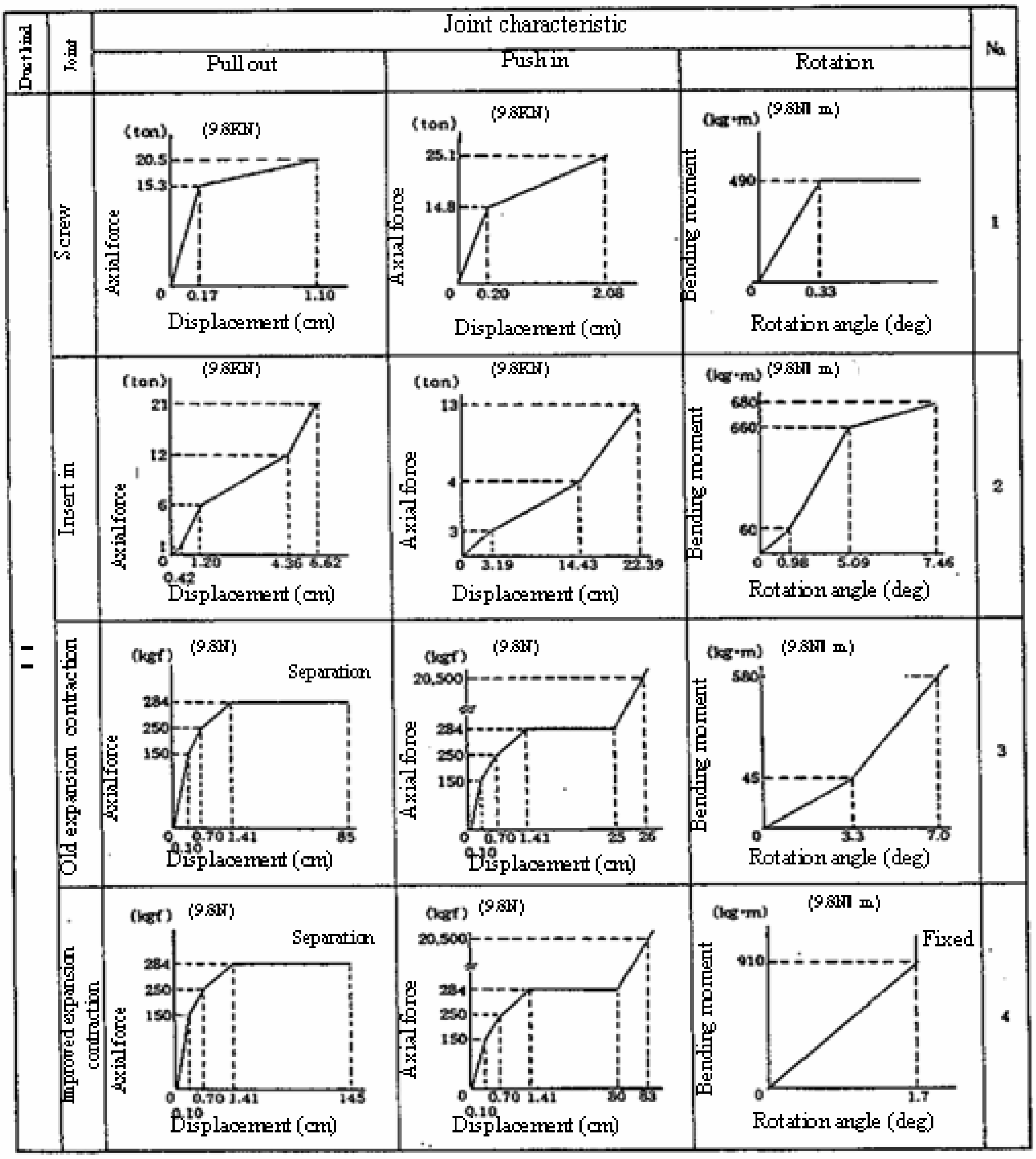
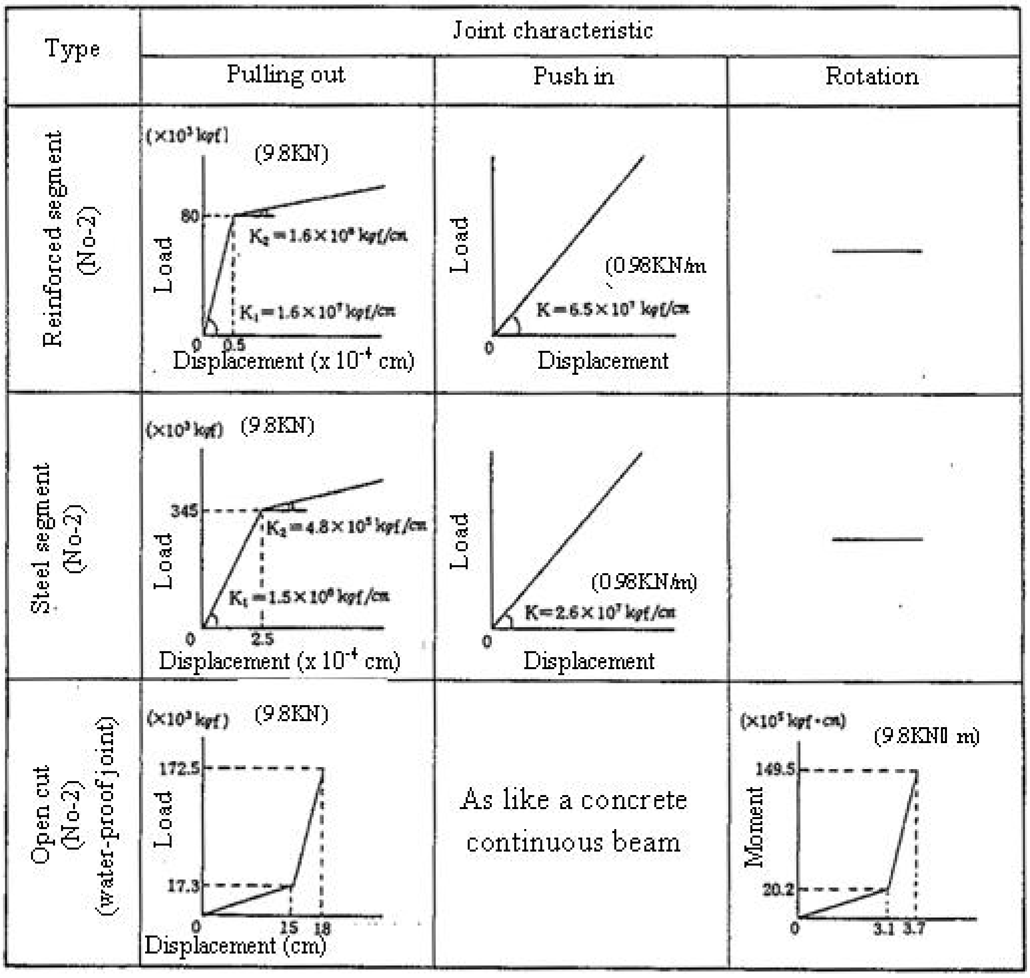


Table 8. Joint part characteristics of shield and open-cut cable tunnels



Followings are ground spring stiffness [3][4][5].

- Settlement in soft ground

Soil spring in settlement ground: K=2.72/3, K'=0.0272/3

- Lift up by liquefaction

Soil spring in liquefied ground: K=2.72/1000 (Linear)

- Liquefaction- vertical displacement

Soil spring in settlement ground: K=2.72/10, K'=0.0272/10, δ=40.0

- Liquefaction horizontal displacement

Soil spring in liquefaction ground: K=2.72/10 (Linear)

Unit of above numbers are N/cm^3

3.3 Calculation method of probability of seismic safety reliability

Response simulation can give a curve of response values for maximum stress, joint displacement and rotation angle depending on input ground displacements.

The probability of seismic safety reliability is obtained depending on seismic inputs of ground displacements as follows:

1) Ground displacement is divided as shown in Table 9.

Table 9. Width range of ground displacement (Unit: cm)

Ground displacement	Divided width range					
Soft ground subsidence	0 - 5	5 - 15	15 - 30	30 - 50	50 -	
Ground crack	0 - 5	5 - 15	15 - 30	30 - 50	50 -	
Vertical replacement at liquefaction	0 - 5	5 - 15	15 - 30	30 - 50	50 - 80	80 -
Horizontal displacement at liquefaction	0 - 10	10 - 30	30 - 60	60-100	100 -	

2) Ground displacement (S_B) corresponding to allowable values (**δ_B**) for pipeline, conduit and shield is obtained.

3) Normal distribution of the ground displacement is assumed in the range of (S_i, S_{i+1}) .

$$S = \frac{1}{\sqrt{2\pi\sigma}} \exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\},\ \sigma = (S_{i+1} - S_i)/2$$

4) Failure probability P_i in (S_i, S_{i+1}) is given as a normal distribution and reliability probability of seismic safety is $1\text{-}P_i$.

The reliability probability is calculated depending on ground classification and seismic intensity level as shown in Tables 3 and 4. However, zero or one probability of structures is given for liquefaction buoyancy force due to deterministic force.

Table 10. Failure stress of pipeline cable tunnel

Duct kind	Failure stress (KN/cm^2)
PS, SA	35
I	20
Id	40
W	5
C	0.3
AP	1.4

Open cut tunnel	4.5

Table 11. Allowable value of joint part (pipeline)

Duct kind	**Joint**	**Limit value**	
		Pull lout (cm)	**Rotation (deg)**
SA	Lead	1.3	-
PS	Screw	1.1 E – 1	0.33
	Insert in	0.66	-
I	Lead filled	1.3	-
Id	Screw	0.2	9.91
	Screw	2.8 E - 2	1.08
	Insert	1.18	14.15
V	T S	-	-
	R R	5.0	-
AP	Simplex	4.0	6.0

Table 12. Allowable value of general part (manhole attached part)

Pipeline kind	**Parts**	**Allowable value**	
		Pull out (cm)	**Rotation (deg)**
PS	Old expansion and contraction	8.5	-
	New expansion and contraction	14.5	-
	Duct sleeve	15.0	-
Id	Duct socket	-	-
	Old expansion and contraction	14.0	-
	New expansion and contraction	14.5	-

	Old expansion and contraction	15.0	-
	Duct socket	-	-
V	Duct sleeve	15.0	-

3.4 Allowable value for pipeline and cable tunnel

Table 10 gives failure stress of pipeline and conduit and allowable joint displacement and rotation angle are set by using Table 11,12 and 13. Allowable joint separation displacement of the shield cable tunnel is fixed as 3 mm and corresponding axial force.

3.5 Probability of the seismic safety reliability of pipeline and cable tunnel

3.5.1 Pipeline

The reliability probability can be obtained by comparing the response values with the allowable values. On the other hand, telecommunication pipelines are buried in multi-step and multi-column which cause different performance of the pipes in upper and lower positions. The probability is obtained for different position pipes. Analyzed results are summarized as follows.

The probability of seismic safety reliability is very high for wave propagation and liquefaction buoyancy. However, the probability is becomes lower for large level of seismic input of liquefaction vertical settlement and lateral flows.

Also, the probability of seismic safety reliability shows lower values for concrete and asbestos pipeline, and also for screw and lead stuffed joint. The probability of seismic safety reliability in upper pipes is lower values compared with down pipes in the multi-step pipe construction [1][12][13].

Table 13. Allowable value of joint parts (No-2 Open -cut tunnel)

Pull out (cm)	**18.0**
Insert in (cm)	-
Rotation (deg)	3.7

3.5.2 Cable tunnel

The probability of seismic safety of the cable tunnel is obtained by response analyses for standard section of structures, and the response values for other sections are modified by multiplying the conversion coefficients to the standard sections.

Response values of No. 1, 3 and 4 cable tunnels are obtained based on the results of No.2 response analysis by using next formula.

$$R_i^{Lique} = \frac{R_i^{Soft\ ground\ subsidence}}{R_2^{Soft\ ground\ subsidence}} \times R_2^{Lique}$$

(R : Response value i : Type number of cable tunnel)

On the other hand, response values of shield cable tunnel by wave propagation is modified by comparing results by response displacement method and by ERAUIL.

i) Solution by response displacement method using equivalent rigidity of ring connection bolts
ii) Analysis for two kinds of RC-No.2 and RC-No.3 considering non-linear behavior of ring connecting bolts by using ERAUL
iii) Modification of response values by following equations

$$R_i = K \cdot R^r_i \ , \ K = R^E_2 / R^r_2$$

(r=Solution in seismic deformation method, E=Analytical solution by ERAUL)

Moreover, Response of shield cable tunnel is decreased following 1st order response mode of shear vibration of the surface ground layer. Results show that the reliability of the shield cable tunnel and open cut cable tunnel are very high compared with those of buried pipelines.

4. SEISMIC RELIABILITY OF CABLE

Figure 5 shows the flow of calculation of the probability of seismic reliability of the cable [10].

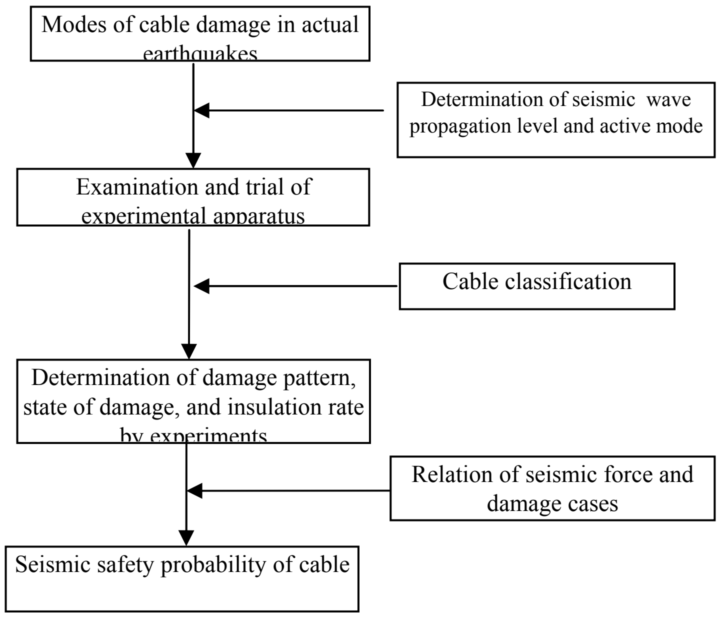


Fig. 5. Calculation flow of cable reliability

4.1 Transformation experiment of cables

Figure 6 shows the deformation process of the cable during a seismic force based on past damage data.

1) Pipe joints are damaged and pulled out by ground deformation.
2) One side of the separated pipes moves in a right-angled direction to the axis.
3) The moving pipe moves to an axial direction by aftershock.

The cable is deformed in the above processes 2) or 3), and reliability can be obtained according to the deformation of the cable.

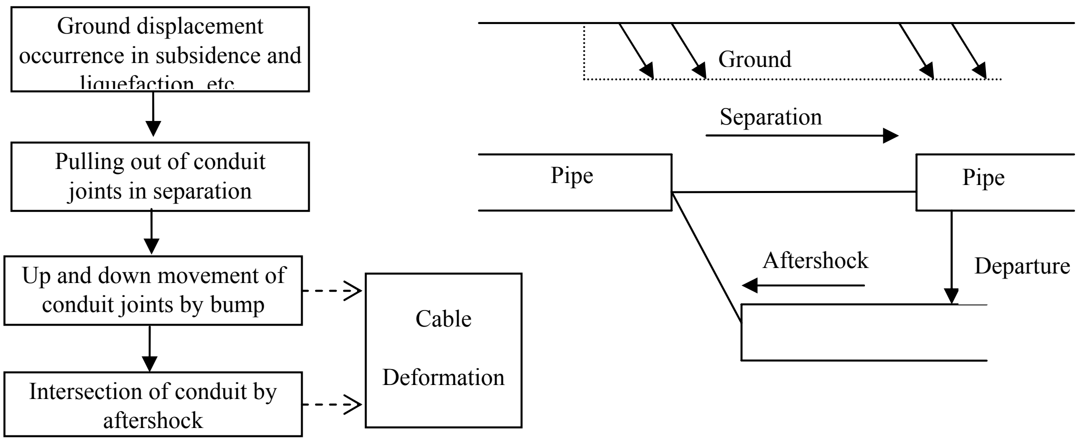


Fig. 6. Deformation mechanism of cables

4.2 Calculation technique of seismic safety probability of cable

Seismic reliability of the cable is divided into next three ranks depending on its usability and serviceability.

Rank 1: When the cable bends, and it doesn't return to the origin (excessive deformation of cable);

Rank 2: When the cable coating breaks by the impact at the edge of the conduit, and gas leakage is caused;

Rank 3: When the cable bends extremely.

It is classified into four areas shown in Figure 7 by the movement zone of the separating pipeline. That is, Area 1 is the case when pipeline shift is small, Area 2 is when cable bends to obtuse angle, Area 3 is when cable bends to right angle and Area 4 is when cable bends to acute angle as shown next.

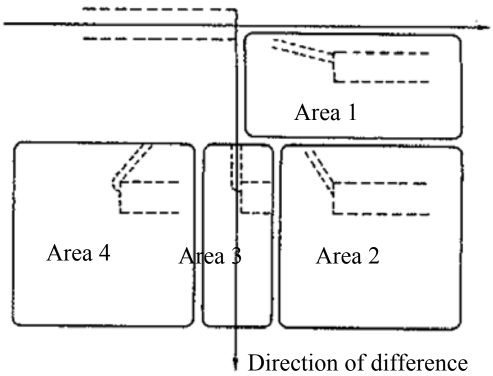


Fig. 7. Classifications of moved pipeline position

- Seismic wave propagation → Area 1
- Vertical displacement during liquefaction → Area 2
- Soft subsoil subsidence and ground fissure→ Area 2 and Area 3
- Subsidence behind bridge abutment and the collapse of fill ground→ Area 2 and Area 3
- Horizontal displacement during liquefaction→ Area 2, Area 3, and Area 4

The seismic safety probability of the cables is totally obtained by considering these ground situations with the experimental results.

5. CONCLUSIONS

Present paper has proposed to evaluate the probability of seismic safety reliability of buried telecommunication facilities. The target facilities are pipelines, cable tunnel and cables. The results are summarized as follows.

1. The probability of seismic reliability is very high for wave propagation and liquefaction buoyancy. However, the probability is becomes lower for large level of seismic input of

liquefaction vertical settlement and lateral flows.

2. The probability of seismic reliability shows lower values for concrete and asbestos pipeline, and also for screw and lead stuffed joint.
3. The reliability of upper pipes is lower values compared with down pipes in the multi-step pipe construction.
4. The reliability is a little less in connected pipes to building structures then general straight pipes
5. Results show that the reliability of the shield cable tunnel and open cut cable tunnel are very high compared with those of buried pipelines.
6. The reliability of cables contained in PVC pipes is high and its tendency is typical in PVC with larger diameter.
7. The reliability of cables become lower under ground settlement and liquefaction lateral flow.

Further researches will be needed for applying the developed methodology to existing buried telecommunication systems, and also for making up countermeasures of seismic safety of facilities and restoration strategies.

REFERENCES

1. Takada S, Higashi S, Tanaka T. Investigation and dynamic analysis on the performance of sewage FRPM pipelines during the Great Hanshin-Awaji Earthquake, Proc. of 3rd China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering, 1998, pp. 173-181.
2. Kuwata Y, Takada S, Nakao M. Seismic risk evaluation and renovation method of weak water supply pipeline to hospital, Proceedings of the 8th US NCEE Paper No-466, 2006.
3. Takada S, Aiwen L. Photograph of pipeline damage crossing fault in recent earthquake, Research group on fault and buried pipelines, 2003.
4. Technical Standard for Petroleum Pipelines, Japan Road Association, 1974.
5. Recommended Standards for Earthquake-Resistant Design of Gas Pipelines, Japan Gas Association, 1982.
6. Design Guidelines for Utilities Tunnel, Japan Road Association 1986.
7. Takada S. Ichihara d, Shinohara M. Seismic performance and design of buried two layered renewal pipelines, Joint Workshop on US-Japan Cooperation Research in Urban Earthquake Disaster Mitigation, Dec. 19, 2003, pp. 81-92.
8. Takada S, Kuwata Y, Tanaka Y, Fukushima S, Katagiri S. An investigation on the fracture of water distribution polyethylene pipeline due to large landslide during the 2004 Niigata Chuetsu Earthquake, Proceedings of the 5 th China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering, pp-129-137, Haikou, China, 2007.
9. Takada S, Katagiri S. A method for evaluation the anti-seismic performance of buried pipelines taking into account the effort of dynamic fracture in non-uniform ground, Proc. of 4th China –Japan-Us Trilateral Sympo. On Lifeline Earthquake Engineering, 2002, pp. 99-106.
10. Koike T, Takada S, Ogawa Y, Matsumoto M, Tajima T, Hassani N. Seismic damage

prediction for the gas distribution systems in greater Iran, 13th World Confernce on Earthquake, B.C., Canada, August 1-6, No-3394, 2004.

11. Kuwata Y, Takada S, Ivanov R. Estimation of allowable fault displacement for pipelines and countermeasures, Proceedings of Pipelines 2005, ASCE, 2005, pp. 674-685.
12. Takada S, Nakano M, Tani K, Kobayashi K, Katagiri S. Development of new rubber ring joint for U-PVC pipeline to increase earthquake resistant performance, IWSA International Workshop, 1998, pp. 153-158.
13. Ivanov R, Takada S, Morita N. Analytical assessment of the vulnerability of underground jointed pipelines to fault displacements, 13th World Confernce on Earthquake Engineering, B.C., Canada, August 1-6, 2004.