Seismic Stability of Geosynthetic-Reinforced Soil Integral Bridge Evaluated by Shaking Table Test

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ABSTRACT

A series of shaking table tests were performed using sinusoidal input motions in a wide range of frequency on small-scale models of: 1) integral bridge; 2) geosynthetic-reinforced soil integral bridge; and 3) nail-reinforced soil integrated bridge. The results were analyzed in the framework of the damped single-degree-of-freedom theory. It is shown that both of integrating the girder to the facing and reinforcing the backfill with geosynthetic layers or nails connected to the abutments/facings increase significantly the seismic stability due to: 1) an increase in the initial natural frequency; 2) a decrease in the decreasing rate of the natural frequency during shaking; 3) an increase in the dynamic strength; and 4) an increase in the damping ratio.

INTRODUCTION

The conventional type bridge comprises typically a girder simple-supported by a pair of abutments via a pair of bearings, movable and fixed (or hinged), and the unreinforced backfill. A number of conventional type bridges failed and collapsed during many previous earthquakes. The authors [1] proposed a new type bridge, called Geosynthetic-Reinforced Soil Integral Bridge (GRS-IB), for new construction that can alleviate a number of technical problems with the conventional type bridge. The GRS-IB is constructed as follows: 1) a pair of geosynthetic-reinforced retaining walls is constructed with a help of gravel-filled gabions or expanded metal mesh boxes placed at the shoulder of each 30 cm-thick

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soil layer; 2) after the major part of the potential deformation of supporting ground and backfill has taken place, thin (with a thickness of 30 cm or more) lightly steel-reinforced full-height rigid facing is constructed by casting-in-place concrete in such a way that it is firmly connected to the reinforcement layers (i.e., geogrid layers); and 3) a continuous girder is constructed integrated to the top of the facings. Referring to the GRS-IB technology, it has been proposed to reinforce an existing conventional bridge by reforming to a Nail-Reinforced Soil Integrated Bridge (NRS-IB) as follows. Firstly, the backfill is reinforced with two layers of large-diameter (typically 40 cm in diameter) nails connected to the top and bottom of respective abutments. Then, the girder is integrated to the top of the abutments ([7] - [9]). The nails have a central metal or FRP tendon covered with cylindrical in-place-cement-mixed soil.

In the previous studies by the authors and their colleagues ([1] - [9]), a series of shaking table tests were performed on small models of GRS-IB and NRS-IB, as well as conventional type bridges, conventional type integral bride and other types, all having about 50 cm-high model abutments. They used sinusoidal input motions at a frequency of 5 Hz of which the acceleration amplitude stepwise increased. They found that the dynamic stability of a bridge increases with: 1) a decrease in the initial value of the dynamic response ratio, M, via an increase in the initial natural frequency (i.e., an increase in the initial stiffness); 2) a decrease in the decreasing rate of the natural frequency (i.e., a decrease in the decreasing rate of the stiffness) during dynamic excitation: i.e., with an increase in the dynamic ductility; 3) a decrease in the M value just before and at the start of failure via an increase in the damping energy dissipation capacity; and 4) an increase in the response acceleration at failure (i.e., an increase in the dynamic strength). They also found that the dynamic stability of GRS-IB and NRS-IB is very high, because the integration of the three major bridge components (the girder, the abutment and the backfill) greatly contribute to all these four factors listed above. Besides, the potential problems by cyclic displacements at the top of the abutments by seasonal thermal deformation of the girder (i.e., settlements due to the active failure in the backfill and elevation of the lateral earth pressure in the passive mode on the back of the facings/abutments) can also be effectively alleviated by reinforcing the backfill with geogrid or nail layers connected to the facings/abutments.

In the present study, to confirm a high dynamic stability of GRS-IB and NRS-IB under more general dynamic loading conditions, another series of shaking table tests were performed using input sinusoidal motions in a wide range of frequency (5 - 20 Hz) on the same small models as the previous studies. The test results were analysed in the framework of the damped single-degree-of-freedom theory as in the previous studies.

SHAKING TABLE TESTS

The shaking table tests were conducted under the gravitational force. The models were constructed inside a rectangular sand box (205.8 cm in length × 60 cm in width × 140 cm in height) (Figure 1). The supporting soil layer and backfill were produced by air-pluviating air-dried Toyoura sand (G_s = 2.65, e_{max} = 0.970, e_{min} = 0.602, D_{50} = 0.179 and U_c = 1.64) to a relative density, $D_r \approx 90$ %. The assumed

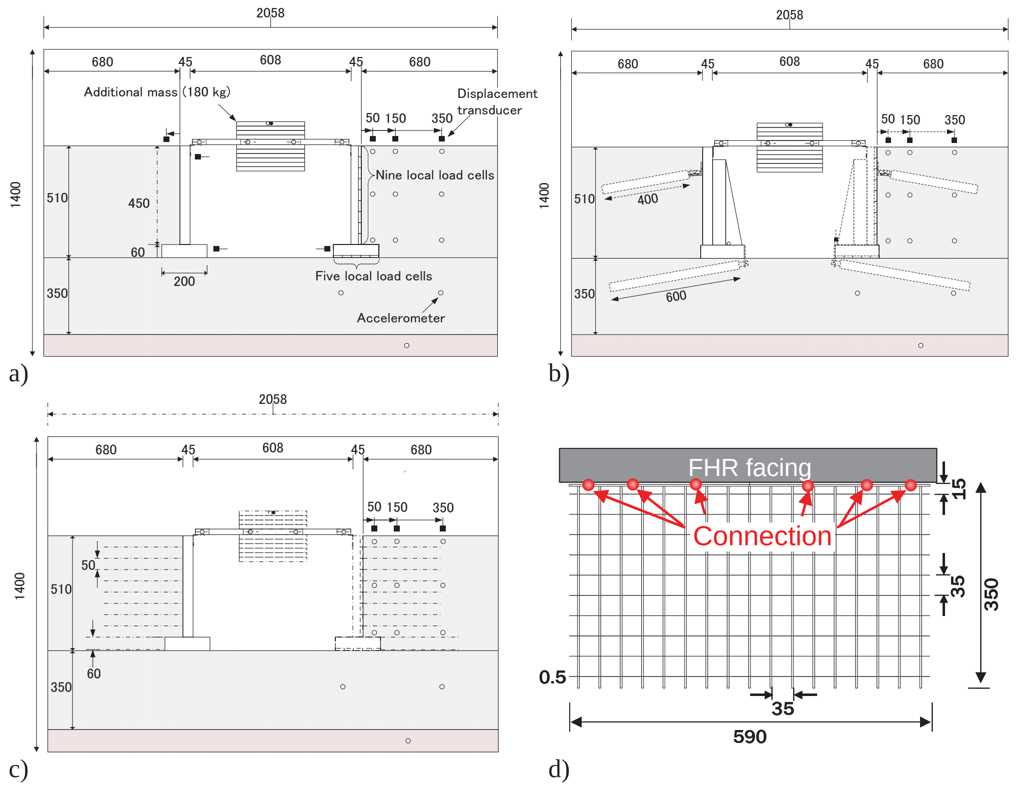

Figure 1. Bridge models; a) conventional integral bridge; b) NRS-IB; c) GRS-IB; and d) model geogrid for GRS-IB model.

length scale 1/λ was 1/10. A 200 kg steel mass was fixed to the centre of the model girder to simulate a 2 m-long model girder (i.e., 20 m in the assumed prototype). The dynamic behaviour of these models is different from their conceived prototype structures due to a reduced length scale, 1/λ= 1/10. It was considered, however, that the comparative behaviour of the models is representative of the one of their conceived prototypes.

With all the models, the girder was connected to the top of the abutments or facings by using a pair of L-shaped stainless steel plate, which started yielding before the start of failure of the models. With Integral Bridge (IB) model, the backfill was not reinforced. In each side of GRS-IB model, ten model geogrid layers were arranged in the backfill with eight layers connected to the facing at a vertical spacing of 5 cm and two layers to the footing at a vertical spacing of 6 cm. The model geogrid was made of phosphor-bronze and Toyoura sand particles were glued on its surface. Although the stiffness of the model geogrid is significantly higher than the one that satisfies the force similitude, the ultimate pullout strength is slightly lower than the one that satisfies the force similitude. The NRS-IB model was made by connecting a pair of gravity-type abutments and the girder of the conventional-type bridge in the same way as the other two models (shown in Figs. 1a & b). Four model nails were arranged in the backfill and supporting ground layer on each side (therefore eight model nails in the whole of the model). Two 40 cm-long nails were connected to the abutment and the other two having a length of

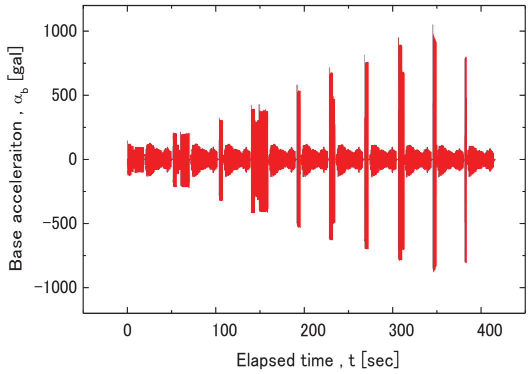

Figure 2. Typical acceleration record for shaking table test in this study

TABLE I TYPICAL EXCITATION STAGES FOR SHAKING TABLE TESTS

stage	1	2	3	4	5	6	7	8	9	10
f_i [Hz]	*5*	*10*	*20*	*2*	*sweep*	*5*	*10*	*20*	*2*	*sweep*
a_b [gal]	*100*					*200*				*100*

stage	11	12	13	14	15	16	17	18	19	20
f_i [Hz]	*5*	*sweep*	*5*	*10*	*20*	*2*	*sweep*	*5*	*sweep*	*5*
a_b [gal]	*300*	*100*	*400*				*100*	*500*	*100*	*600*

stage	21	22	23	24	25	26	27	28	29	30	31
f_i [Hz]	*10*	*sweep*	*5*	*sweep*	*5*	*10*	*sweep*	*5*	*10*	*sweep*	*5*
a_b [gal]	*600*	*100*	*700*	*100*	*800*		*100*	*900*		*100*	*1000*

60 cm to the bottom of the abutment via pin connectors. The model nails were hollow brass cylinders simulating prototype large-diameter nails with a diameter of typically 40 cm, developed to have large pullout strength when used in un-cemented soil ([10]). The density of the model nail is similar to the value of the prototype, about 2.0 g/cm^3, and the diameter is 4 cm, which is one tenth of the one of the prototype. The abutments of the NRS-IB model, the full-height rigid facings of IB and GRS-IB models and the footings of these models were made of duralumin with a density of 2.79 g/cm^3. The surfaces in contact with sand were made rough with sandpapers.

The input motion consisted of twenty sinusoidal waves at each stage in a wide range of input frequency, f_i = 5 – 20 Hz. The amplitude of input acceleration, α_b, was increased stepwise by 100 gals (cm/sec^2). A sweep test with f_i = 5 – 20 Hz at α_b = 100 gals was repeated in between the respective two successive stages to evaluate the process of structural softening of the models in the course of dynamic loading. A typical input wave history is shown in Figure 2 and TABLE I.

TEST RESULTS

By using Equations 1 & 2 (according to the damped single-degree-of-freedom theory), the transient values of the natural frequency, f_0, and the damping ratio, ξ, for each cycle of the respective bridge models were back-calculated from respective sets of observed values of the dynamic the response ratio M = α_t/α_b, (i.e., the ratio of the amplitudes of acceleration at the girder and the table) and the phase difference between the table and response accelerations, φ:

$$M = \sqrt{\frac{1+4\xi^2\beta^2}{(1+\beta^2)^2+4\xi^2\beta^2}} \tag{1}$$

$$\tan\varphi = \frac{-2\xi\beta^3}{1-(1-4\xi^2)\beta^2} \tag{2}$$

where β is the tuning ratio, f_i/f_0.

Natural Frequency

Figures 3a, 4a and 5a show the relationships between the natural frequency, f_0, and α_b, The initial value of f_0 is about 20 Hz with all the models. This means that the backfill reinforcement does not function effectively when the deformation of the backfill remains small. The f_0 value decreases with an increase in the number of loading cycle at each stage and with an increase in α_b. These trends are rather independent of f_i other than 2 Hz, at which the f_0 value tends to be lower than the values at higher f_i values. This is due likely to that, at smaller f_i values, for the same α_b value, the response displacements, therefore the strains, in the model become larger and, therefore, the response of the model becomes softer. The decreasing rates of f_0 of GRS-IB and NRS-IB models are similar while noticeably larger than IB model. This is due to that the reinforcement becomes more effective as the model deformation increases.

These results show that the first two of the four advantageous factors of GRS-IB and NRS-IB are also valid for a wide range of input frequency.

Tuning Ratio and Acceleration Response Ratio

With a decrease in f_0 for a given f_i value, $\beta = f_i/f_0$ increases while the resonant state where $\beta \approx 1.0$ (Figures. 3b, 4b and 5b) is approached with $M = \alpha_t/\alpha_b$ increasing at an increasing rate (Figures 3c, 4c, and 5c). With an increase in f_i for the same f_0 value, β becomes larger and the resonant state is reached at smaller α_b values. For these reasons, when f_i = 20 Hz, the resonance state is reached and passed at relative low α_b values without exhibiting the start of failure. On the other hand, when f_i = 2 Hz, β remains much lower than 1.0 and the resonance state is not reached even after α_b becomes relatively large. When f_i = 5 Hz and 10 Hz, β approaches 1.0 and the resonance state is reached after α_b becomes relatively large. Therefore, the failure starts when the resonant state is reached. With GRS-IB and NRS-IB models, for the same f_i, the resonant state is reached at similar α_b values and these α_b values are higher than with IB model. This trend of behaviour is due to that reinforcing the backfill becomes very effective when the model starts exhibiting relatively large deformation at the start of failure.

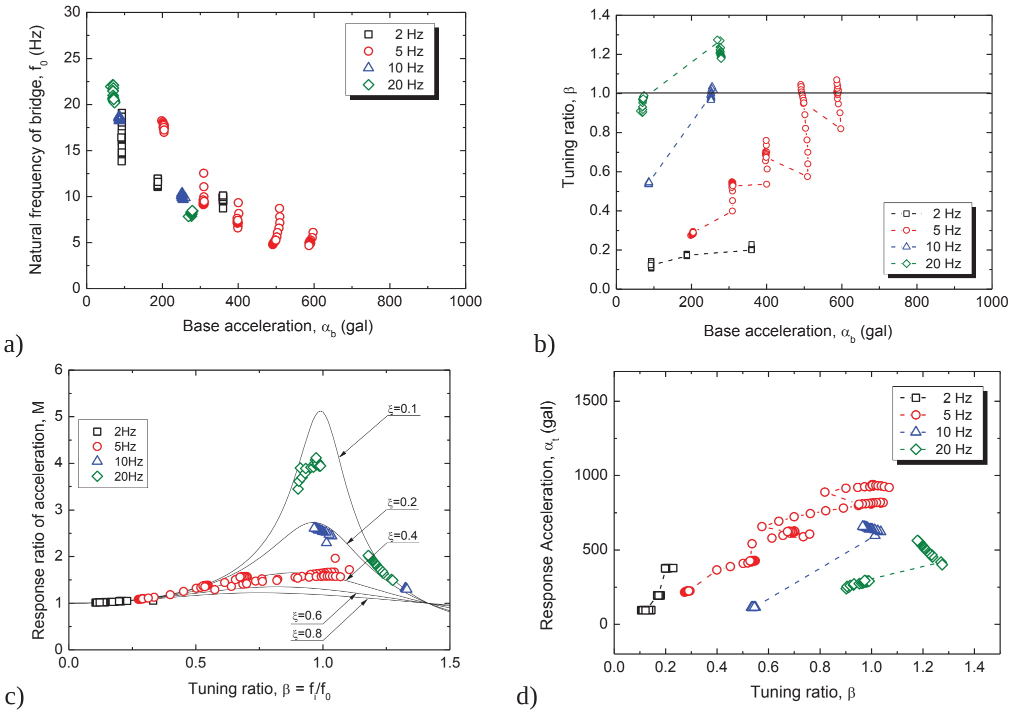

Figure 3. a) f_0-α_b; b) β-α_b; c) M-β; and d) α_t-β relations, integral bridge (IB)

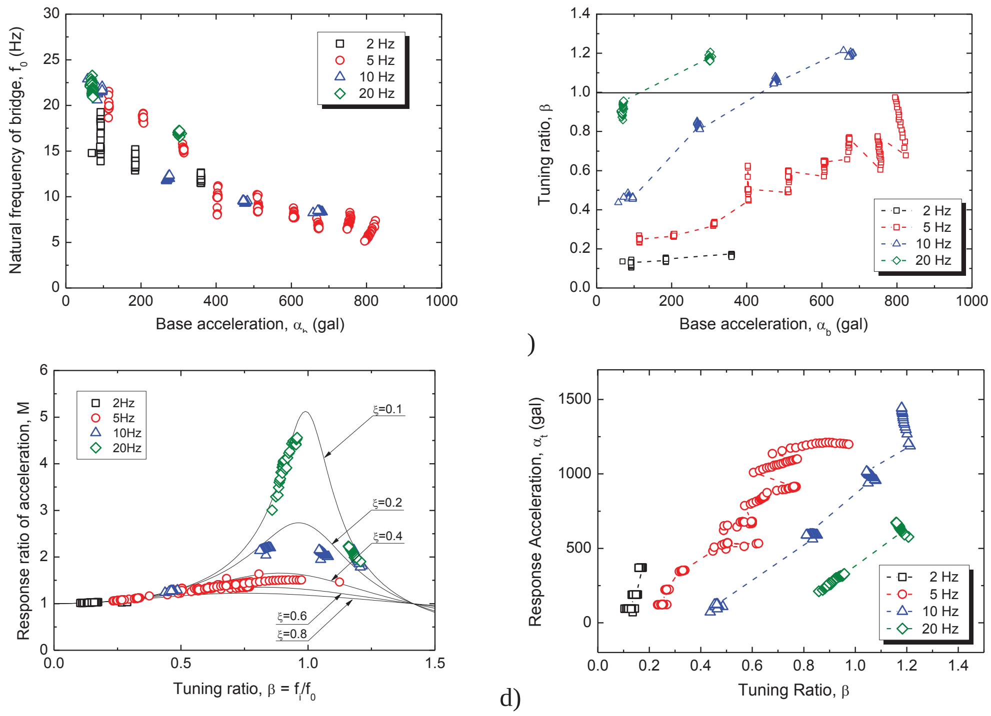

Figure 4. a) f_0-α_b; b) β-α_b; c) M-β; and d) α_t-β relations, GRS-IB

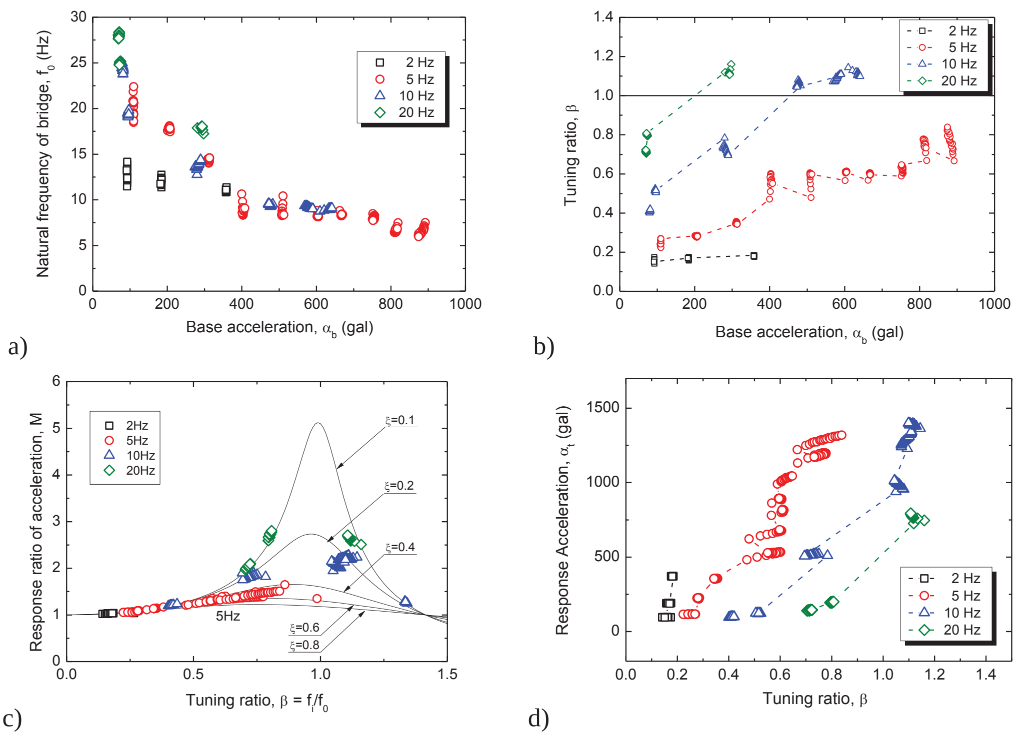

Figure 5. a) f_0-α_b; b) β-α_b; c) M-β; and d) α_t-β relations, NRS-IB

Figures 3d, 4d and 5d show the relationships between the response acceleration, α_t, and the tuning ratio, β. All the models starts failing at the resonance state (where M becomes the maximum) when f_i = 5 Hz, at which the α_t value at the resonant state becomes largest among the different f_i values. This state is reached when $\alpha_b \approx$ 500 gals and $\alpha_t \approx$ 800 gals with IB model; $\alpha_b \approx$ 750 gals and $\alpha_t \approx$ 1100 gals with GRS-IB model; and $\alpha_b \approx$ 730 gals and $\alpha_t \approx$ 1080 gals with NRS model. This result indicates that the dynamic strength in terms of the α_t value at the start of failure is similar with GRS-IB and NRS-IB models while much larger than IB model.

The damping ratio, ξ, at the resonance state is around 0.5 with GRS-IB model and around 0.5 with NRS model, which are larger than 0.4 with IB model. This means that the dynamic energy of the girder and the facings/abutments dissipates into the backfill and the supporting ground more easily with GRS-IB and NRS-IB models than with IB models. This is due to that the contact between the facings/abutments and the backfill and supporting ground is maintained much better by reinforcing the backfill with reinforcement connected to the facings/abutments.

These results show that the last two of the four advantageous factors of GRS-IB and NRS-IB are also valid for a wide range of input frequency.

SUMMURY

The model test results presented above show that, with both of the new bridge types (i.e. GRS-IB and NRS-IB), both of structural integration of the girder and the abutments/facings and reinforcing of the backfill with geogrid or nail layers connected to the abutments/facings all contribute to the evolution of high initial stiffness, high dynamic ductility, high dynamic strength and high damping. Then, the natural frequency can always be kept much higher than the predominant frequency of ordinary earthquake motions conceived in design, then the response acceleration is kept very low. This trend of behaviour is more enhanced by a higher damping ratio. Besides, the failure is made difficult to start due to a high dynamic strength. In this way, the seismic stability becomes very high for a wide range of input frequency.

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