Appendix

Details of Bridge Nonlinear Modeling and NLTHA Implementation

The bridge nonlinear modeling and nonlinear time-history analysis were implemented as follows. A linear finite element model of the track-bridge structure was first established using ANSYS, incorporating beam elements (BEAM188) for the girders and piers, and spring-damper elements (COMBIN14) for the bearings, shear grooves, fasteners, and other connection components. The local nonlinear correction method was then employed to incorporate the nonlinear hysteretic behavior of key components (e.g., bridge bearings) without updating the global stiffness matrix. The elastic-perfectly plastic (EPP) model was adopted for the bearings, with the hysteretic displacement governed by a differential equation. The yield force and yield displacement for fixed and sliding bearings were defined based on typical design specifications. Geometric nonlinearity, including P-delta effects, was not considered, as the pier height (14 m) is moderate and the selected ground motions primarily induce responses within the elastic or mildly inelastic range. The numerical time integration was performed using the unconditionally stable explicit CQ3 algorithm, which ensures computational efficiency for large-scale nonlinear VTB systems. The large stiffness method was employed for seismic input to enforce ground motion displacements at the supports. Based on the above methodology, the entire program was implemented in MATLAB.

Table A1

Descriptive statistics of original and generated datasets with 3× augmentation

Index	Mean	SD	Min	25-percentile	50-percentile	75-percentile	Max
PGA	0.1210	0.1933	0.0034	0.0345	0.0760	0.1384	1.6982
	0.1757	**0.3024**	**0.0034**	**0.0449**	**0.0912**	**0.1684**	**1.6982**
PGV	0.0072	0.0097	0.0003	0.0023	0.0043	0.0077	0.0604
	0.0094	**0.0138**	**0.0003**	**0.0027**	**0.0047**	**0.0090**	**0.0604**
PGD	0.0028	0.0046	2.7E-5	0.0005	0.0013	0.0036	0.0299
	0.0034	**0.0058**	**2.8E-5**	**0.0006**	**0.0014**	**0.0040**	**0.0299**
FR1	0.0796	0.0741	0.0208	0.0422	0.0588	0.0877	0.4619
	0.0714	**0.0695**	**0.0003**	**0.0372**	**0.0530**	**0.0805**	**0.4619**
FR2	0.3724	0.2655	0.0755	0.1688	0.3056	0.4440	1.1799
	0.3482	**0.2564**	**0.0002**	**0.1479**	**0.2924**	**0.4275**	**1.1799**
a_RMS	0.0182	0.0352	0.0009	0.0072	0.0120	0.0189	0.3400
	0.0268	**0.0580**	**0.0010**	**0.0074**	**0.0129**	**0.0215**	**0.3400**
v_RMS	0.0015	0.0016	0.0003	0.0006	0.0009	0.0019	0.0093
	0.0018	**0.0020**	**0.0003**	**0.0006**	**0.0011**	**0.0020**	**0.0093**
d_RMS	0.0008	0.0012	7.0E-6	0.0001	0.0004	0.0013	0.0080
	0.0010	**0.0015**	**7.1E-6**	**0.0001**	**0.0004**	**0.0013**	**0.0080**
IA	0.0049	0.0260	4.1E-6	0.0002	0.0006	0.0020	0.2542
	0.0112	**0.0442**	**4.1E-6**	**0.0002**	**0.0009**	**0.0029**	**0.2542**
IC	0.0205	0.0757	0.0001	0.0028	0.0070	0.0157	0.7347
	0.0387	**0.1274**	**0.0002**	**0.0030**	**0.0078**	**0.0165**	**0.7347**
SED	0.0001	0.0004	2.3E-8	8.4E-6	2.8E-5	0.0001	0.0028
	0.0002	**0.0005**	**2.3E-8**	**1.1E-5**	**3.2E-5**	**0.0002**	**0.0028**
CAV	0.3132	0.4301	0.0089	0.1026	0.1973	0.3594	3.1249
	0.4146	**0.5941**	**0.0089**	**0.1085**	**0.2331**	**0.4586**	**3.1249**
CAD	0.0328	0.0367	4.3E-4	0.0093	0.0179	0.0522	0.2279

	0.0369	**0.0398**	**4.4E-4**	**0.0101**	**0.0191**	**0.0554**	**0.2279**
Td	13.490	6.6971	1.5600	8.4500	12.095	16.335	32.380
	12.990	**7.2614**	**0.6965**	**7.8925**	**11.680**	**16.335**	**32.380**
PSA	0.5136	0.8795	0.0126	0.1559	0.2882	0.6219	8.0254
	0.7484	**1.3958**	**0.0126**	**0.1837**	**0.3418**	**0.7007**	**8.0254**
PSV	0.0230	0.0253	0.0006	0.0087	0.0157	0.0302	0.1748
	0.0291	**0.0352**	**0.0007**	**0.0094**	**0.0174**	**0.0351**	**0.1748**
PSD	0.0080	0.0103	0.0001	0.0018	0.0041	0.0120	0.0576
	0.0089	**0.0116**	**0.0001**	**0.0018**	**0.0044**	**0.0129**	**0.0576**
EPA	0.0917	0.1177	0.0030	0.0347	0.0591	0.1065	0.8023
	0.1250	**0.1715**	**0.0031**	**0.0367**	**0.0693**	**0.1310**	**0.8023**
EPV	0.0051	0.0059	1.4E-4	0.0016	0.0033	0.0062	0.0334
	0.0063	**0.0078**	**1.4E-4**	**0.0019**	**0.0035**	**0.0070**	**0.0334**
EPD	0.0019	0.0028	2.1E-5	0.0003	0.0010	0.0023	0.0180
	0.0022	**0.0030**	**1.6E-5**	**0.0004**	**0.0011**	**0.0028**	**0.0180**
HI	0.0271	0.0308	0.0006	0.0094	0.0186	0.0317	0.1788
	0.0338	**0.0410**	**0.0006**	**0.0102**	**0.0201**	**0.0392**	**0.1788**
Tg	0.4018	0.2716	0.1116	0.2401	0.3217	0.4506	2.1212
	0.3686	**0.2579**	**0.0429**	**0.2233**	**0.3011**	**0.4216**	**2.1212**
Hz	3.7518	3.8220	0.1441	1.2289	2.3721	4.8361	21.270
	4.3363	**4.7584**	**0.0964**	**1.2422**	**2.4453**	**5.2252**	**21.270**
CAI	0.0218	0.0350	0.0001	0.0023	0.0075	0.0241	0.2018
	0.0253	**0.0418**	**0.0001**	**0.0025**	**0.0102**	**0.0241**	**0.2018**
Sa(T1,ξ)	0.0776	0.0892	0.0013	0.0237	0.0509	0.0894	0.4843
	0.0922	**0.1074**	**0.0014**	**0.0293**	**0.0567**	**0.1088**	**0.4843**
Sv(T1,ξ)	0.0129	0.0149	0.0002	0.0039	0.0087	0.0145	0.0950
	0.015	**0.0188**	**0.0003**	**0.0047**	**0.0092**	**0.0182**	**0.0950**
Sd(T1,ξ)	0.0019	0.0022	3.4E-5	0.0006	0.0012	0.0022	0.0122
	0.0023	**0.0027**	**3.5E-5**	**0.0007**	**0.0014**	**0.0027**	**0.0122**
SMA	0.1077	0.1728	0.0033	0.0327	0.0663	0.1270	1.5290
	0.1566	**0.2731**	**0.0033**	**0.0417**	**0.0804**	**0.1466**	**1.5290**
Max_Fy	22.871	0.0693	22.689	22.837	22.863	22.894	23.141
	22.861	**0.0737**	**22.681**	**22.826**	**22.861**	**22.887**	**23.141**
Max_Fz	147.96	0.1407	147.72	147.92	147.96	147.99	149.09
	147.99	**0.2168**	**147.73**	**147.91**	**147.97**	**148.00**	**149.09**
Max_Dy	2.6062	0.6642	2.1505	2.3508	2.4058	2.7678	8.1569
	2.7958	**1.0446**	**2.1506**	**2.3509**	**2.4269**	**2.7759**	**8.1569**
Max_Dz	13.594	0.1324	13.489	13.547	13.558	13.580	14.229
	13.629	**0.1686**	**13.490**	**13.551**	**13.562**	**13.609**	**14.229**

Table A2
Optimized hyperparameter configurations for peak response prediction models

Index Algorithm	Hyperparameters	Range	Peak Response Optimization Result
DT	Minimum Leaf Size	1-20	8
RF	Number of Trees	10-300	10
	Minimum Leaf Size	1-50	1
SVM	Box Constraint	0.01-100	6.0171
	Kernel Scale	0.001-100	4.7435
	Epsilon	0.001-10	0.0292
MLP	Layer Number	1-3	2
	Size of Layer	10-300	23 / 12
	Regularization Coefficient	1e-05-0.1	0.0093
GRNN	Spread	0.01-10	9.7799
LSTM	Layer Number	1-3	2
	Size of Layer	10-300	47 / 16
	Dropout rate	0.001-0.5	0.05469
GRU	Layer Number	1-3	2
	Size of Layer	10-300	42 / 17
	Dropout rate	0.001-0.5	0.1225
CNN	Stride Number	1-3	2
	Size of Feature	10-100	39 / 38
TCN	Number of Convolutions	6-64	48
	Size of Kernel	2-10	7
	Number of Blocks	1-3	2
	Dropout rate	0.001-0.5	0.1083
RBF	Kernel Scale	0.001-100	1.6393
	Epsilon	0.001-10	3.7265
BiLSTM	Layer Number	1-3	2
	Size of Layer	10-300	39 / 10
	Dropout rate	0.001-0.5	0.1069
Transformer	Positional Encoding	0-6	2
	Head / Keys	1-64	16 / 32
	Size of Layer	4-256	128
	Dropout rate	0.001-0.5	0.0254
	Learning Rate	0.001-0.1	0.0073
OURS	Layer Number	1-3	2
	Size of Layer	10-300	46 / 17
	Dropout rate	0.001-0.5	0.0648
	Box Constraint	0.01-100	0.2396
	Kernel Scale	0.001-100	2.0046
	Epsilon	0.001-10	0.0422