The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

A displacement-control design for structures and earthworks in a high-seismic site

A. Micheli, C. Catinari, F. De Maio, E. Mittiga & G. Ricci
Anas S.p.A., Direzione Progettazione e Realizzazione Lavori, Rome, Italy

ABSTRACT: The paper is dedicated to the approach for a road design in a geotechnically complex site in Emilia-Romagna (Northern Italy) Region where, due to poor soil mechanical properties and geomorphological configuration were identified favorable conditions for massive local seismic amplification phenomena. After the seismic amplification evaluation, carried out with a specific software by using a one-dimensional Local Seismic Response (RSL) analysis model, design seismic action has been defined. RSL analysis main output was a very high peak ground acceleration (PGA) and a displacement evaluation approach (Newmark method) has been carried out to design both structures and earthworks evaluating the maximum relevant displacement. Soil characterization, both for stratigraphy and for mechanical properties, has been carried out starting from soil investigation data. Of evidence, dynamic soil properties have been derived from purpose-designed laboratory test (Resonant Column Test) and on-site tests (Down-Hole geophysical tests).

1 INTRODUCTION

The reference case study is given by earthworks and structures design for a new road alignment of National Road n.9 (S.S. 9 Emilia) to avoid the urban centre of the community of Castelbolognese, in Northern Italy. Increase of road traffic along the present road alignment has brought an addition of unsustainable pollution for the citizens; for this reason, local Authorities and Anas S. p.A (Italian Authority for Roads) decided to design an alternative route surrounding the city centre. The project consists of a new secondary infrastructure C1 type (according to DM 05/11/2001 Italian code) for a total length of approximately 3.3 km including 4 roundabouts, 1 railway overpass, 1 road underpass, 2 hydraulic and road bridges. Moreover, design road alignment includes very high road embankment (up to about 12 m) close to a railway overpass.

Geological context is represented by *Supersintema Emiliano-Romagnolo*, a stratigraphy macro unit which includes quaternary deposits of continental origin outcropping at the Apennines margin and related sediments contained in the underground of Po valley. This unit is represented by alluvial deposits with water table approximately at the ground level; such deposits are composed by an alternance of silty clays in the most superficial portions of the soil, medium sand and silty sand, passing to soft silty sands with depth. Slightly hard silt clays are located 15-16 meters deep from surface. More than 25 meters from surface, deposits show better mechanical properties.

Italian Building Code at present in force (NTC 2018) has not been adopted for reference during design phase, as it was still in definition; therefore, the project referred to the previous NTC 2008 Italian Building Code.

2 GEOTECHNICAL MODEL

2.1 *Geotechnical and geophysical investigation surveys*

During the different levels of design, two investigation surveys were carried out to execute laboratory and field tests. Aim of the first survey (2008) was to provide a large-scale view of

Table 1. Geotechnical survey: available boreholes

Survey	Borehole	Length (m)	Borehole Instrumentation	n° of undisture dsample	n° of disturbed sample
2016	S1	30	Down-Hole	3	2
2016	S2	30	Down-Hole	5	–
2016	S3	30	Standpipe Piezometer	3	–
2016	S4	30	Down-Hole	4	2

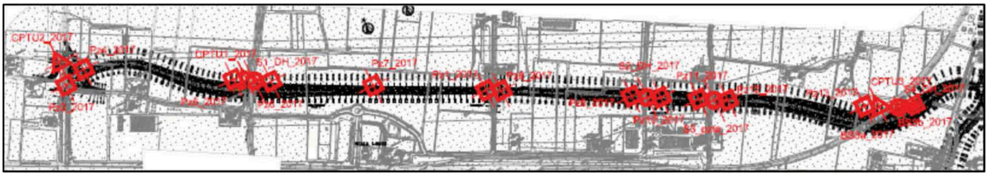

Figure 1. Position of the boreholes along the road design

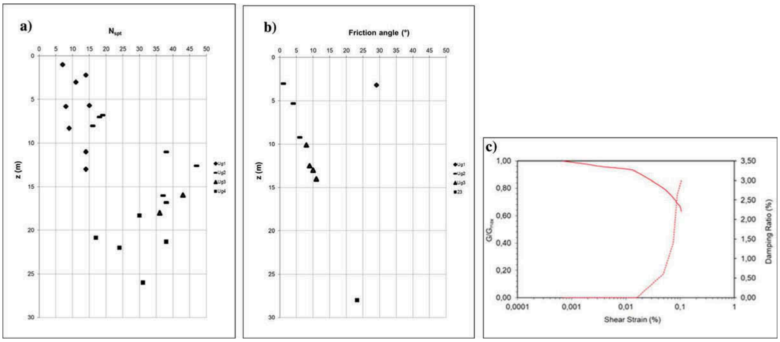

Figure 2. N_{SPT} values (a), friction angle values from laboratory tests (b) and results of laboratory Resonant Column Test for medium sand/silty sand lithotype

the subsoil able to assess stratigraphic reconstruction, hydraulic condition and of physical and mechanical properties of lithotypes; the second survey (2016-2017) let to complete geotechnical model refining mechanical characteristics, completely identifying the pore water pressure and providing dynamic characteristic of lithotypes. Depth of boreholes cannot reach the seismic bedrock but geological studies confirm that bedrock itself is not less than 50 meters depth. In Table 1 are summarized general informations from the second survey and Figure 1 show position of boreholes along the road design.

On the samples taken have been conducted 15 oedometer tests, 3 direct shear test, 6 unconsolidated-undrained test (TxUU), 5 consolidated-undrained test (TxCU), 5 consolidated-drained test (TxCD), 1 resonant column test, in addition to granulometric analysis and Atterberg limit soil classification. The only standpipe piezometer installed in the borehole S3 has identified the water table at 3 m from the ground level.. Field test consist of 24 Standard Penetration Test, 5 Piezometer Cone Penetration Test, 3 Down-Hole and 5 Seismic Refraction Test. Figure 2 shows respectively some results of field test and laboratory test.

2.2 *Geotechnical model*

Knowledge acquired based on survey results allowed to delineate the layout of the stratigraphy and of the geotechnical characteristics of the identified lithotypes, from which the physical and mechanical parameters were obtained.

Table 2. Physical, mechanical and deformability parameters

Lithotype	γ (kN/m^3)	E_{ed} (MPa)	E' (MPa)	c' (kPa)	φ' (°)	c_u (kPa)
Ug1	19	10	7.5	5	28	50
Ug2	19	25	18.6	0	32	-
Ug3	19	30	22.4	0	35	-
Ug4	19	15	11.2	10	30	$60+0.22\sigma'_v$

In particular, four lithotypes are been recognized:

- Unit *Ug1*: slightly hard cohesive silty loamy deposit;
- Unit *Ug2*: medium sand/silty sand;
- Unit *Ug3*: medium and large sized gravel;
- Unit *Ug4*: hard cohesive clayey silt.

Mechanical properties and deformability parameters (estimated from in situ tests at large strain level) are summarized in Table 2:

3 SEISMICITY OF THE AREA

3.1 *Historical seismicity*

In order to evaluate the seismic action it is necessary to have information on the historical and recent seismicity of the project area.

The information regarding the seismic events occurred around project area were obtained from the last version of the Italian Macro-seismic Database DBMI15. In Figure 3 main seismic events occurred in Castelbolognese are represented. In terms of seismic intensity (Mercalli-Cancani- Sieberg Scale), the most significant earthquake was occurred in Faentina area with a magnitude M_w of 6.12 and produced effects of 7° of MCS scale.

On May 2012 an earthquake of magnitude M_w 5.9 struck the Po Valley with epicenter in the Province of Modena and hypocenter estimated at a depth of 6.3 km.

3.2 *Local seismic response*

3.2.1 *Seismic classification according to NTC 2008*

Seismic hazard has been defined using Italian Building Code through the peak ground acceleration on stiff horizontal outcropping bedrock (a_g), as well as in terms of ordinate of the corresponding elastic response spectrum for a predetermined exceedance probability P_{VR} on a reference period V_R.

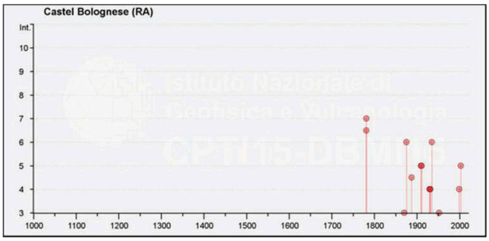

Figure 3. Representation of significant seismic events occurring at Castelbolognese in the years (x-axis) between 1000-2014

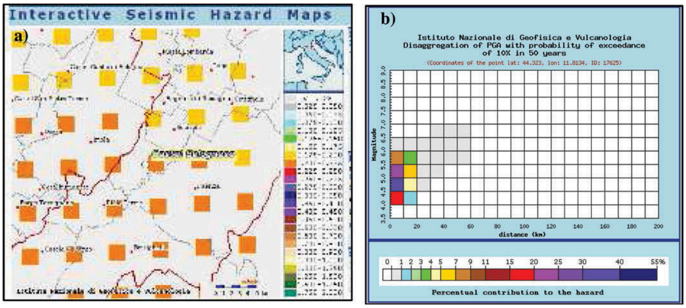

Figure 4. Istituto Nazionale di Geofisica e Vulcanologia (INGV): maps of the seismic hazard of Emilia Romagna (a) and disaggregation graph of PGA with probability of exceedance of 10% in 50 years.(b)

According to Italian Building Code (NTC 2008), in order to increase the degree of accuracy in the prediction of the seismic motion, a local seismic response analysis based on recorded natural accelerograms was carried out.

3.2.2 *Seismic hazard disaggregation*

After the definition of seismic hazard, it is necessary to identify the local amplification of the seismic impulse produced by the actual characteristics of the soil.

The evaluation of the seismic hazard has been carried out by consultation of public data of Istituto Nazionale di Geofisica e Vulcanologia (INGV). The obtained parameters are calculated using geographical co-ordinates of the site of borehole S4_2016, located near the areas object of local seismic response. Figure 4 represents the map of the project area with the indication of the reference grid points related to the acceleration on bedrock with a probability of exceedance of 10% in 50 years, as described in Italian Code.

INGV data provide disaggregation graphic in terms of magnitude, source distance and ε; these parameters refer to the seismic event with the higher probability to determine the PGA value with reference to a certain occurrence likelihood. The disaggregation graph indicates the magnitude M_w and the source distance R whose medium values are $M_{w\ medium}$=4.93 and R_{medio}=6.57 km.

In order to obtain spectra in accordance to NTC 2008, natural accelerograms related to the horizontal component are selected by using for the source distance range of $0<R<20$ km and for magnitude range of $4.0<M_W<6.0$ for SLV. In this case, software REXEL (Iervolino I. et al., 2009), developed by the academic project Reluis, has been consulted. In particular, seven recorded accelerograms have been selected as a function of magnitude and epicentral distance; these accelerograms were scaled to the acceleration value a_g on outcropping bedrock and horizontal ground level.

Figure 6 shows the spectrum-compatibility check; the average spectrum, in the range of 0.2-2.0s of period, differs from the target spectrum no more than 10%.the standard deviation of average spectral ordinate is always inside the range 0.2-2.0s of period compared to the corresponding component of the target elastic spectrum.

Evento	Waveform ID	Data	Mw	Epicentral Distance [km]	PGA_X [m/s^2]	PGA_Y [m/s^2]	PGV_X [m/s]	PGV_Y [m/s]	Site class
Lazio Abruzzo	365	07/05/1984	5.9	5	0.985	10,802	0.0368	0.0365	A
NE of Banja Luka	5655	13/08/1981	5.7	10	0.7302	0.7398	0.0606	0.0337	A
Izmit (aftershock)	1243	13/09/1999	5.8	15	0.7138	3,112	0.0551	0.1454	A
Valnerina	242	19/09/1979	5.8	5	15,095	20,121	0.0758	0.1401	A
SE of Tirana	3802	09/01/1988	5.9	7	11,132	40,372	0.0501	0.1361	A
Friuli (aftershock)	981	16/09/1977	5.4	11	0.6393	0.9099	0.0485	0.0713	A
Mt. Hengill Area	5085	04/06/1998	5.4	15	0.1199	0.1714	0.0188	0.0234	A

Figure 5. Characteristics of selected accelerograms

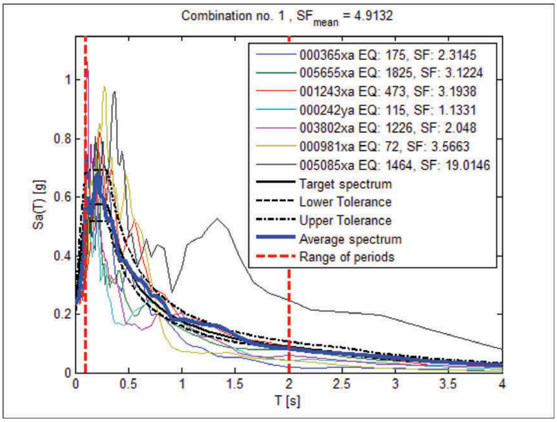

Figure 6. Comparison between average spectrum and target spectrum from NTC 2008

3.2.3 *Methodological approach*

Local seismic response analyses (RSL) were performed in free-field conditions using complete natural accelerograms actually recorded on site and providing value of the reference acceleration on outcropping bedrock.

After selection of spectrum compatible accelerograms according to NTC 2008, seismic characterization was performed with a series of analyzes in order to evaluate the seismic local response in a one-dimensional field in the hypothesis of equivalent linear visco-elastic behavior; this one-dimensional problem has been analyzed adopting equivalent linear approach of software EERA (Bardet et al. 2000).

Table 3. Seismic soil model

Lithotype	Thickness (m)	γ (kN/m^3)	$V_{s\ medium}$ (m/s)
Ug1	10	19	220
Ug2	6	19	270
Ug4	34	19	350
Seismic bedrock	-	22	850

Horizontal layer assimilated by a one-dimensional system locally characterizes the reference seismic soil model adopted for RSL, itself deduced from geotechnical and geophysical investigation. Shear modulus reduction curve and damping ratio are been assumed for silty clay soil

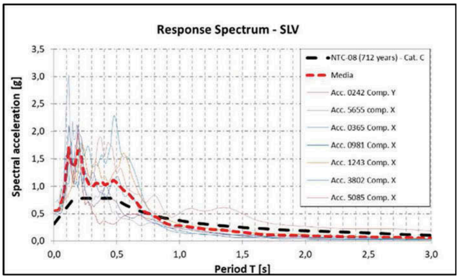

Figure 7. Response spectrum calculated in correspondence of borehole S4_2016

from results of resonant column test while for sandy silt soils has been utilized curves of literature (Seed & Idriss, 1970).

The result of calculation, i.e. the response spectrum for SLV, is represented in Figure 7:

4 APPLICATION OF A DISPLACEMENT-CONTROL DESIGN: THE CASE STUDY OF S.S. 9 “EMILIA”

4.1 *Design general seismic approach*

From the analysis of average spectrum calculated from the local seismic response, it can be noticed that at T=0 PGA is equal to 0.551g while the maximum acceleration value reaches more than 1.6g. Spectrum calculated as described showed that in the range of period compatible with frequencies of structure and earthworks (0<T<0.5) seismic loads would be very high. A typical design approach would have led to massive dimensioning of structures and earthworks with consequent economic overburden.

A different approach was carried out thanks to generally fair mechanical properties of the uppermost layers of soil (soil type Ug1) and the precise evaluation of the seismic motion through the local seismic response analysis. Structures were designed with raft foundations and earthworks were designed without any soil reinforcement or other specific features. A similar approach in design of structures and earthwork, therefore, was applied through evaluation of critical displacements during earthquake. Displacement evaluations were carried out using Newmark’s method, as described in the following in the case of a road embankment.

4.2 *Displacement-control design: Newmark’s method applied to a road embankment*

Stability analyses of road embankments are performed with the traditional method of global limit equilibrium outlining soil as rigid-plastic material and adopting Mohr-Coulomb failure criterium; in this case, Bishop’s method has been utilized using SLOPE/W as calculation software.

Detailed design contain three calculation sections representatives of the entire project; in this paper are shown the results of section n.145 only, corresponding to a railway overpass (Castelbolognese-Ravenna railway). The embankment is 10.5 meter high and width of top

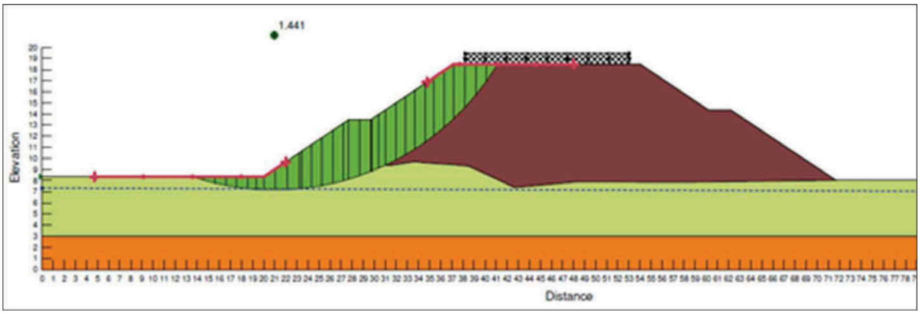

Figure 8. Critical slip surface and factor of safety

Table 4. Summary of stability analyses – Section 145 – static condition

Section	pk	z (m)	Lithotype	Height (m)	FS static
145	2+647	0 - 5	Ug1	10.50	1.441
		5 - 7	Ug2		

embankment is 16 m; the width of sloping portion of embankment is 17 m, divided by a berm of 2 m. Traffic load of 20 kPa has been considered in the static analyses according to the combination of reference NTC 2008. Figure 8 shows the critical slip surface and factor of safety using the entry-exit technique implemented in the software while Table 4 shows a summary of slope analyses.

Under seismic conditions has been adopted a displacement-control method (Newmark procedure); this method is based on the idea that during an earthquake there may be temporary inertial force that cause the block to slide down the incline. The corresponding permanent deformation is the accumulation of the short sliding instances caused by a critical acceleration ac defined as ac=kcg where kc is acceleration factor.

In terms of safety factor FS, a_c corresponds to the acceleration able to produce a FS=1 in a pseudo static slope stability analysis. The meaning of critical acceleration is shown in Figure 10 which represent accelerogram and horizontal line corresponding to the a_c of potential sliding mass. If the accelerogram contains a lower peak than the critical acceleration, no

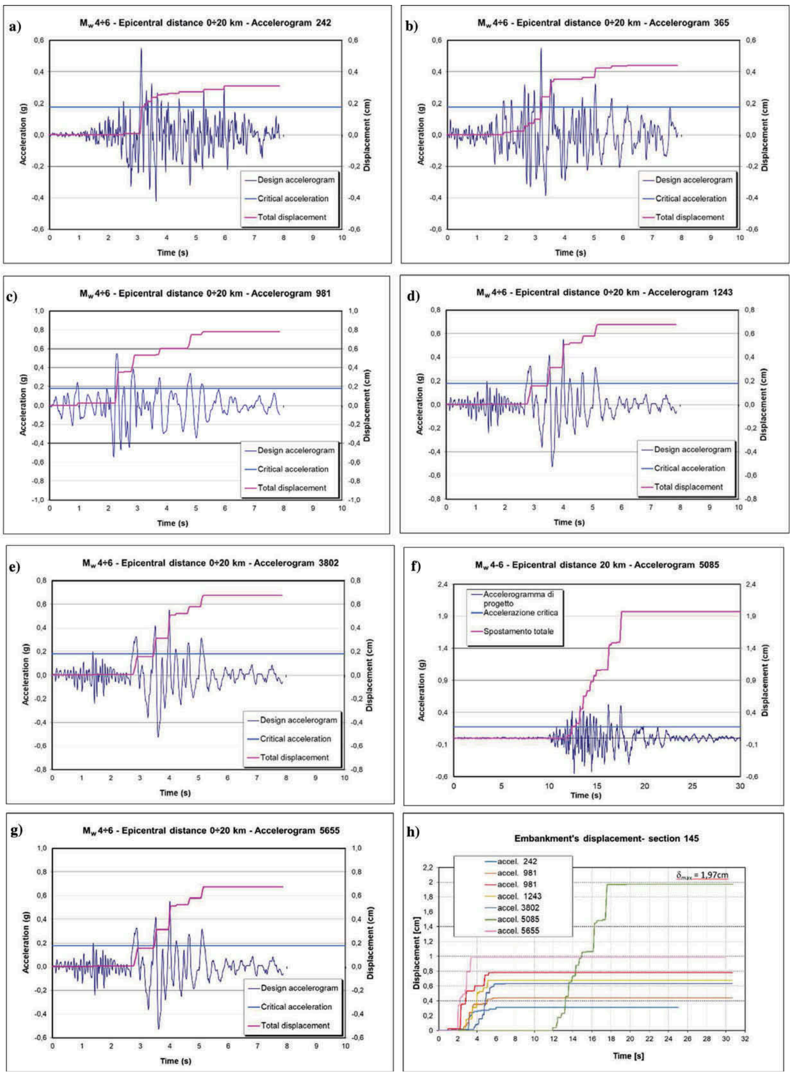

Figure 9. a)-g) Total displacement for every single natural accelerogram h) Total embankment's displacement

Table 5. Acceleration factor k_c and expected displacement

	Expected displacement							
Section	k_c	acc. 242	Acc. 365	Acc.	Acc.1243	Acc.3802	Acc.5085	Acc.5655
145	0.1769	0.31	0.44	0.781	0.674	0.636	1.972	0.986

relative displacement between the sliding mass and the slope base will occur. In the opposite case, this method provides for the integration of the accelerogram area placed above the critical acceleration value determining velocity and relative (permanent) displacement of the block.

The calculation of the critical acceleration factor kc was performed adopting global limit equilibrium approach using SLOPE/W: in particular the analyzes described for the static conditions have been repeated introducing an equivalent static horizontal force in order to get the sliding mass into limit conditions characterized by a safety factor equal to 1. Whereas in static condition there are already safety factors equal to 1, the critical acceleration factor k_c is equal to zero by definition. Figures 9 a)-g) shows the acceleration time histories and the total displacement calculated with Newmark's method for each accelerogram.

As it can be noticed in Table 5, the highest displacement refers to accelerogram 5085 and is equal to 1.972 cm, compatible with the serviceability of the road.

5 CONCLUSIONS

In a typical geological contest of Po Valley in Northern Italy a new road alignment over embankments up to 12 meters high has been designed. Earthworks will be founded on a stratigraphy formed by silty clays, silty sand and large sized gravel with water level coincident with ground level. An adequate geological and geotechnical survey has been conducted whose results allowed to define both geological-geotechnical and seismic model of project area. In order to increase the degree of accuracy in the prediction of the seismic motion, a local seismic response analysis based on recorded natural accelerograms was carried out. Thanks to fair properties of the uppermost layers of soil (soil type Ug1), instead of dimensioning massive structures and earthworks, a different approach (displacement-control design) was carried out: structures were designed with raft foundations and earthworks were designed without any soil reinforcement or other specific features maintaining a critical displacement compatible with the serviceability of the road. An application of this approach regarding on road embankments has been described calculating the critical acceleration such that the sliding mass get into limit condition and admitting the displacement induced as functional for the road embankment.

REFERENCES

Geoslope International Ltd 2012 – SLOPE/W, Stability modeling with Geostudio
Iervolino I., Galasso C., Cosenza E. 2009. REXEL: computer aided record selection for code-based seismic structural analysis. Bulletin of Earthquake Engineering, 8:339–362
INGV 2008. Mappe interattive di pericolosità sismica
INGV 2016. Database Macrosismico Italiano 2015, DBMI15
Kramer S.L.1996, Geotechnical Earthquake Engineering
Italian Ministry of Infrastructures and Transport 2002 – Decreto Ministeriale n. 6792 del 05/11/2011
Italian Ministry of Infrastructures and Transport 2008 – Decreto 14 Gennaio 2008, NTC 2008
Italian Ministry of Infrastructures and Trasport 2018 – Decreto 17 Gennaio 2018, NTC 2018
Lai C.G., Foti S., Rota M. 2009. Input sismico e stabilità geotecnica dei siti di costruzione
Nori L., Di Marcantonio P. 2014. Manuale pratico di risposta sismica locale