Seismic waves caused by reinforced concrete decks impacting the ground

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Abstract

In order to comply with the latest European Highway Standards, the highway Salerno - Reggio Calabria, in southern Italy, had do be widened and upgraded to reduce its vulnerability to earthquakes. Reinforced concrete viaducts, no longer needed for the new road, had to be demolished. Many bridges still to be used for the highway required refurbishment due to 50 years of wind, frost and salt corrosion. This refurbishment and new constructions had to be carried out simultaneously. To keep the highway open during the renewal process, all traffic was directed to one side of the road. Demolition was conducted extremely close to operational roadways and viaducts, as close as only 2 cm (0.8 in). Care had to be taken to ensure that the stresses (vibration levels), resulting from the demolished pylons and decks hitting the ground, were below the no-damage thresholds for the nearby acceptors (structures receiving the vibration stresses). These structures including bridges, houses and buried pipelines (water, oil and gas). In some cases, care also had to be taken to preserve the existing pylons supporting decks that were being demolished; since the same pylons were going to be used for the new viaducts (bridges). New continuous decks in weathering steel replaced the old reinforced concrete decks.

There are accurate decay curves available to calculate stresses and vibrations from detonation of explosives. These curves have been validated through years of testing However, we could not find such curves for the impact of large masses onto the earth, so we developed our own physical model. This model was based on the kinetic energy of the impacting mass computed from the potential energy (mass times the height) less a fraction of potential energy being adsorbed in the pulverization of the concrete upon impact to the ground. The value of this kinetic energy being absorbed by the pulverization of the concrete was not easy to compute, so the energy delivered to the ground and subsequent vibration levels were overestimated. These values were evaluated with seismic monitoring. The large number of viaduct demolished along with their seismic monitoring offered ample opportunity to adjust and validate the vibration energy decay rate. The purpose of this paper is to share with other blasters our experience and the vibration energy decay model that we developed, should they be involved in demolition projects adjacent to sensitive structures. Also given is data on the predominant frequencies of the seismic waves, information on the monitoring procedure and the analysis of the referenced seismic event.

Explosives demolition of viaducts

Donor: the decks being cut down generated the seismic waves

The decks were strongly reinforced concrete slabs 20 cm (8 in) thick on 3 or 4 "I" beams, whose height from 1.4 to 2.2 m (4.6 to 7.2 ft) or 2 "V" beams 2 m (6.6 ft) high. The length of the decks ranged from 16 to 45 m (52.5 to 147.6 ft). All of this viaducts were built in the 1960's. Some of them were partially re-reinforced in the 1980's after the strong "Irpinia" earthquake (6.89 on the Richter scale) which left no actual damage on the supporting structural components, example in figures 1 and 2.

Figure 1: a viaduct to be demolished, with its 32 m (105 ft) long decks standing on 2 cylindrical pylons.

Figure 2: viaduct of figure 1, after having been cut down by pylons demolition.

Figure 3: example of viaduct demolition where pylons were left in place to support the new weathering-steel (COR_TEN) continuous deck replacing the reinforced concrete one being demolished.

Acceptors: the structures being impacted by the seismic waves

The acceptors (structures affected) were found to be in close range as follows:

- Operational viaducts and pylons of the viaduct for which the decks were demolished within a distance of some centimeters/inches, see figure 3.
- Residential and business structures within a distance of 25 m (82 ft), see figure 4.
- Pipeline below the decks within a distance of 12 m (40 ft) with more than 3 m (10 ft) of earth cover.
- Steel electricity pylon within 10 m (33 ft).
- Road and railway tunnels within 40 m (131 ft).

Figure 4: decks cut down in the proximity of a residential quarter.

Seismic wave monitoring

Monitoring was conducted according to the DIN 4150-1 of 2001, the DIN 4150-3 of 1999 and the ISEE - Field practice guidelines for blasting seismographs of 2009.

The ground vibration response monitored and the structures were comparable with the DIN 100%-no-damage-thresholds.

To prevent resonance due to overlapping vibrations induced by deck impact, a preliminary dynamic characterization was conducted. By means of an impulsive loading of the predominant vibration frequency at the spot monitored, there was evidence of values much higher than expected from the decks impacting on the ground.

The distance to the measuring spot was measured from the center of gravity of the impacting deck or decks. The geophones were always clamped to the structures by means of threaded bars and an iron strap.

The data considered to compute the decay curve is given in the adjacent table, table 1.

25	37	142	69	142	28	26	27	300	32	1.200	45	8	7	235	143
	0,3	0,5	0,1	0,5	2,6	3,0	1,5	6,0	6,0	78,5	16,0	6,0	1,0	4,6	2,6
	peak ground velocity [mm/s]				frequency zero crossing [Hz]				[m]						
	Vertical	Transverse	Radial	MAX V, T, R	Vertical	Transverse	Radial	Distance R [m]	aver. distance deck to ground	cooperating Weight [ton]	length of deck [m]	height of deck [m]	cooperating Decks [pc]	Impact energy [MJ]	Scaled Distance [m / MJ^0,19]
1	36,50	142,0	54,0	142,0	3	5	5	6	32	266	32	6	1	84	2,6
2	6,20	5,7	6,7	6,7	9	6	3	31	32	266	32	6	1	84	13,5
3	0,25	0,5	0,3	0,5	5	5	5	300	32	266	32	6	1	84	131,1
4	9,40	12,2	16,0	16,0	8	3	2	19	17	266	32	6	1	44	9,3
5	3,30	4,3	2,3	4,3	5	5	6	45	17	266	32	6	1	44	22,1
6	4,30	3,0	3,6	4,3	9	15	14	21	6	78	16	6	1	5	15,8
7	1,50	1,0	2,5	2,5	9	6	10	30	13	78	16	6	1	10	19,5
8	0,63	0,9	0,9	0,9	11	7	7	150	13	78	16	6	1	10	97,5
9	0,66	1,0	0,4	1,0	28	12	9	220	13	78	16	6	1	10	143,0
10	0,51	1,0	1,0	1,0	5	5	6	215	13	78	16	6	1	10	139,8
11	3,80	7,6	6,1	7,6	6	3	7	25	13	447	45	6	1	57	11,7
12	0,31	0,5	0,1	0,5	-	6	-	250	13	447	45	6	1	57	117,4
13	12,00	10,6	12,0	12,0	-	-	-	40	25	549	16	6	7	135	16,0
14	2,41	7,3	3,9	7,3	-	6	6	57	25	549	16	6	7	135	22,8
15	4,70	10,4	0,1	10,4	-	7	-	41	25	549	16	6	7	135	16,4
16	9,14	73,0	69,0	73,0	-	-	-	8	25	549	16	6	7	135	3,2
17	2,54	1,0	3,2	3,2	7	6	6	69	25	549	16	6	7	135	27,6
18	3,56	3,6	7,1	7,1	-	-	-	20	25	549	16	6	7	135	8,0
19	4,69	4,6	8,8	8,8	-	7	7	43	25	549	16	6	7	135	17,2
20	13,21	66,0	6,1	66,0	9	10	4	12	22	266	32	6	1	58	5,6
21	0,51	1,5	1,0	1,5	5	14	27	39	22	266	32	6	1	58	18,3
22	0,95	1,4	0,7	1,4	-	-	-	50	22	266	32	6	1	58	23,4
23	1,71	2,9	0,8	2,9	-	12	-	80	22	266	32	6	1	58	37,5
24	8,63	11,7	9,1	11,7	10	16	15	20	20	1200	41	6	3	235	7,2
25	5,46	7,8	7,9	7,9	16	26	2	25	20	1141	41	8	3	224	9,1

Table 1: data collected to computate the decay curve

Peak vibration versus potential energy

A non precise correlation was expected between the peak vibration velocity at the structure (acceptor) and the "donor's potential energy" (mass of the deck being blasted less the mass demolished, times its height from the point of impact). This approximation will vary due to distance, height of the deck, variation in geology, and the amount of energy adsorbed in the pulverization process as the deck impacts the ground. The same variables will affect vibration levels when blasting. In the same way as the data collected in blast monitoring are "averaged" in a power regression, summarizing the energy decay (at given interval of confidence); so too was the data from the impact on the ground computed in the power regression with vibration velocity as dependent variable and distance and potential energy (instead of explosion energy as for the blast) as independent variables (Y = K * X1^a * X1^b).

Results of the power regression are given in the following for 50% and 95% confidence limits, chart 1:
$v_{MAX(V,R,T)}$ 50% = 184 * (R/E^0,19)^-1,2
$v_{MAX(V,R,T)}$ 95% = 387 * (R/E^0,19)^-1,2
with:
$v_{MAX\ (R,V,T)}$ 50% [mm/s]: the vibration velocity which will be probably (50%) induced at acceptors.
$v_{MAX\ (R,V,T)}$95% [mm/s]: the maximum vibration velocity which can be reasonably (95%) be induced at the acceptors.
R [m]: seismic path from the center of mass of the deck, or decks when cooperating, at impact to the measuring spot;
E [MJ]: impact energy, equal to the potential energy of impacting mass (mass times the height).
Statistics of the regression proof a good correspondence of the measured points cloud to the decay curve, with a correlation coefficient R equal to 0,91, as it is also to be seen from the plot in the log-log chart:

statistics	*x2(E)*	*x1 (R)*
esp. Q | esp. R | val. K	0,22	-1,19
standard error for the coefficients	0,13	0,13
Determ coef. . r²| standard error y	0,825	0,64
Statistic F | degree of freedom	51,97	22

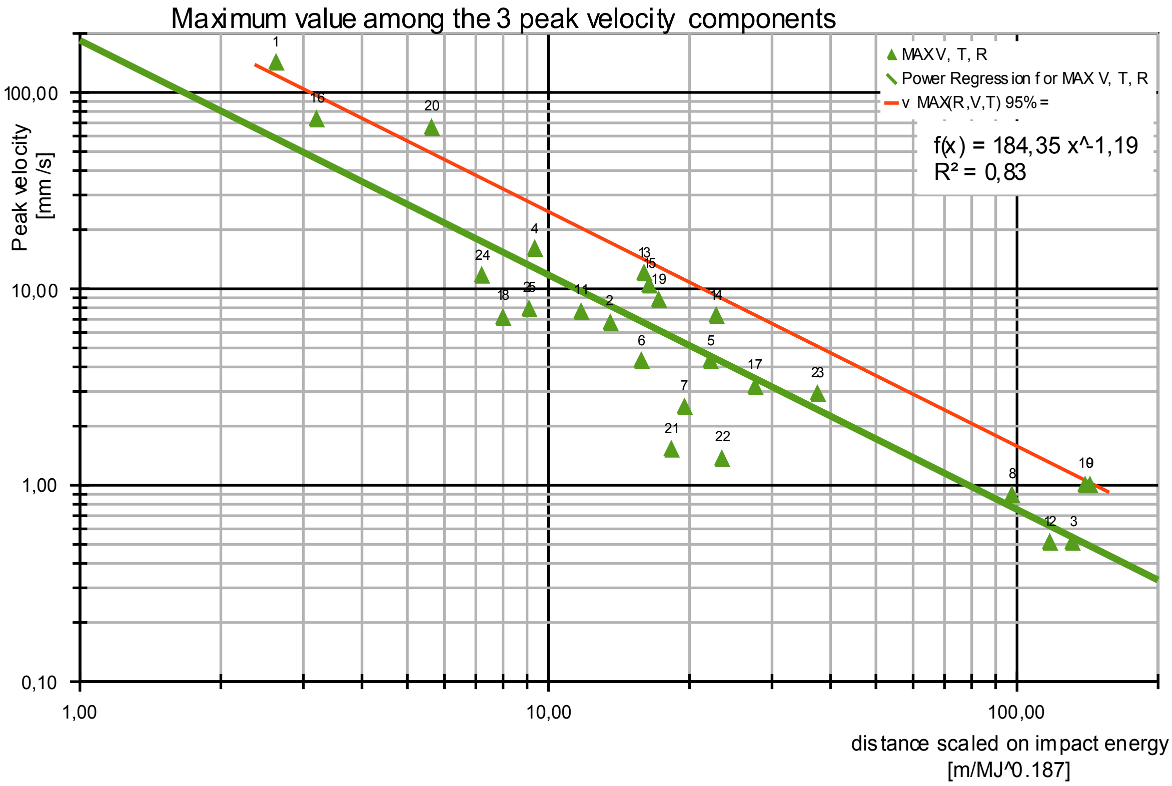

Chart 1: decay curve at 50% and 95% confidence level, of the peak velocity versus distance and potential energy (mass times height of fall).

For example using the decay model, it is possible to predict the energy (peak particle velocity) induced by a 30 meters fall, at a structure 20m (66ft) distance from the impact of a deck / mass of 390 tons (859.802lbs) of reinforced concreteas follows:
3826[1] kN * 30 m = 115 MJ:
$v_{MAX\ (R,V,T)}$ 50% [mm/s]: 184 * (20/115^0.19)^-1,2 = 14.9 mm/s = 0.59 in/s
$v_{MAX\ (R,V,T)}$ 95% [mm/s]: 387 * (20/115^0.19)^-1,2 = 31.4 mm/s = 1.24 in/s
Peak particle velocity induced at the acceptor most likely will not reasonably exceed 31 mm/s, and will probably br closer to 15 mm/s.

Falling decks and seismic waveforms produced

The concrete deck, once it has lost its rigid links to the abutments after the charges are detonated, starts collapsing to the ground. The collapse is delayed momentarily after the blast. Thi is due to the time needed for expansion of the explosion gasses to fill the cracks that were developed by the blast. This delays ranges from tenths of a millisecond in the "I" beams decks to hundredths in the "V" beams decks. We can neglect the resistance of the air to the deck's downward movement due to the short path of only hundred meters. The time (t), in seconds, needed to impact the ground is dependent on the height of the deck (S) in meters, as follow:
t = ((2*S) / 9,81)^0,5.
For a fall of 20m (66ft), the time lapse among the blast and the impact to earth will be about 2seconds. In case of a long sequential blast, with acceptors in the range of 100 meters (330 ft), there will be no overlapping of the seismic wave due to the blast and that due to the impact. At larger distances, due to the gradual transfer of the energy from the high frequency component of the impulsive wave train, to the lower frequency ones, ther is a consequential flattening of the peaks, and an overlapping may be possible especially for shorter height of fall (chart.2).
Seismic waves produced by the blast propagates themselves at a speed of about 3,3 km/s (10800 ft/s) and in the ground among 1800 and 3000 m/s (5900 and 9800ft/s), depending on the nature of the formations and their jointing.

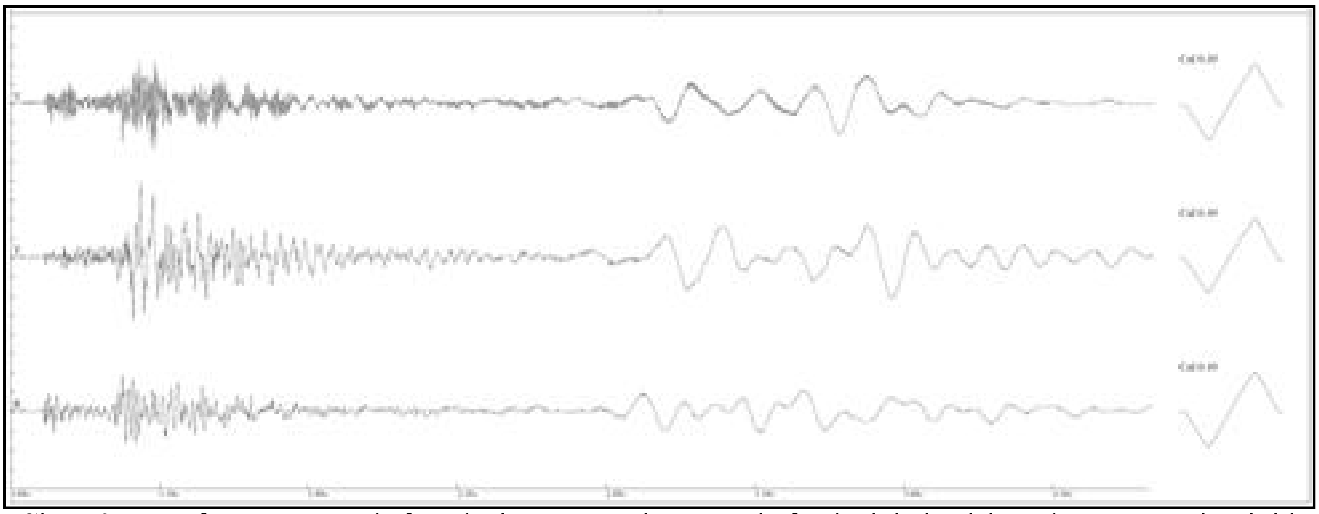

Chart 2: waveform measured after the impact on the ground of a deck being blasted to remove its rigid links from the abutments. Its mass and height from the ground were respectively 44kN e 17m (56ft). The measuring spot was at 45m (148) distance.

1 390 t * 9,81 kN/t

Predominant frequencies in the seismic waves train

Predominant frequencies of the vibration, due to the decks blasted ranged among 35 and 120Hz in the reinforced concrete structure and decayed rapidly while propagating from the point of the blast. Predominant frequencies of the vibration due to the impact of decks on the ground are much lower, ranging among 2 and 28 Hz. These lower frequency waves are closer to those of the structures, and therefore, are more capable of triggering resonance.
The higher the wave frequency is, the lower the associated displacements, thus the vibrations induced by explosions are less dangerous than those induced by the decks' impact on the ground.

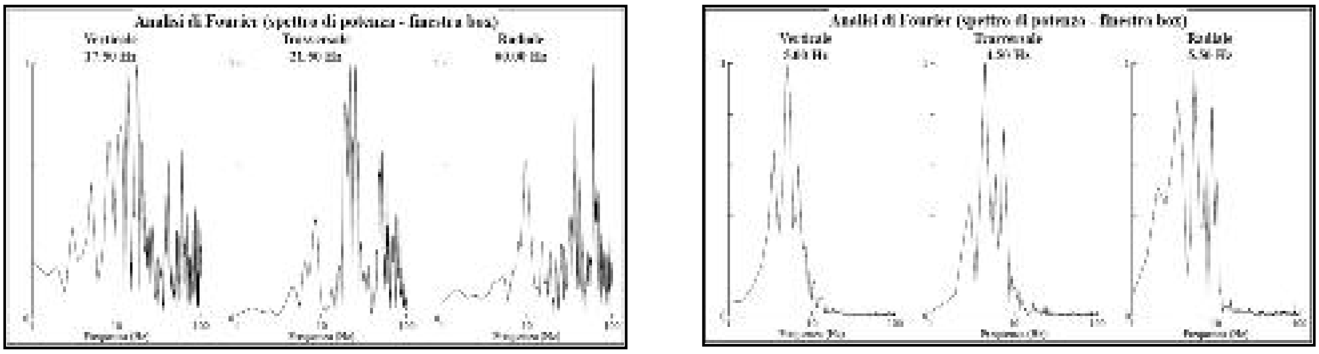

Chart 3: FFT of the wave train due respectively to the blast (set on left) and to the impact on the ground of the above waveform.

Damping cushion

The practice of interposing a damping cushion on the bed of a fall reduces the peak amplitude of vibration velocity at short distances. At medium and long distances, however, it does not significantly reduce the amplitude. Impulse is not reduced at all. This "cushion" slows down the speed of impact and therefore the kinetic energy, reducing the volume of the concrete being crushed by the impact; thus reducing potential energy used to pulverize the deck. The energy transferred to the ground (the pulse) remains practically unchanged if compared to the impact without the cushion. Already at a distance of some tenths of meters, the amplitude of vibration is thus unchanged. Nevertheless, the practice of using a "cushion" to decrease vibration is adopted when structures are in close proximity. This is done to minimize the risks of decks slipping towards structures down the slope and to contain fragmentation.

Conclusion

The decay curve computed on data collected from several bridge demolitions, permits us to extimate, with a good approximation, the peak particle velocity induced at distances in the range of meters to hundreds of meters (feet to several hundreds of feet) when masses in the range of several hundreds of tons are collapsed from heights ranging up to 100 meters. This allows the blaster to have a reliable tool for the preliminary evaluation of compliance with the safety regulations established to prevent structural damage and annoyance to residents.

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