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How Fast Can the Ground Really Move?

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Executive Summary

Strong ground motion from earthquakes has resulted in millions of deaths and trillions of dollars in economic damage. A ground velocity of 1.8 m/sec is generally considered sufficient to cause very heavy damage to structures and lifelines. To date, the largest peak particle ground velocity ever recorded in an earthquake is 3.18 m/sec (Chi-Chi earthquake in 1999), but this does not mean higher velocities are not possible, given the relatively short period of history for which measurements are available.

How high can velocities go in a natural process such as an earthquake near Earth's surface? Are there limits? There is no easy answer; we discuss some clues. Probabilistic analyses sometimes yield very high estimates, well in excess of 10 m/sec, at very low probabilities of exceedance. Many scientists consider such high values physically impossible. Various physical considerations suggest a limit somewhere in the range of 3 to 6 m/sec for near-surface earthquakes. Peak ground velocities observed in the vicinity of nuclear explosions may provide some insight.

As distance from a nuclear explosion source increases, ground motion is governed first by the Hugoniot high-pressure equation of state, then by nonlinear solid deformation, then eventually by quasi-linear elasticity. We suggest that the highest particle velocity near the transition to elasticity indicates the maximum ground velocity possible in a shallow earthquake. Considering data observed in granite, that transition takes place at a scaled range from the explosion source where particle velocity is about 6 to 10 m/sec—suggesting that the current maximum velocity measurement may not represent an absolute physical limit, but rather a limitation in sampling.

Contents

1. Introduction

In this article we discuss approaches to determining the largest possible ground motion during an earthquake occurring near the surface of Earth. The problem is a difficult one. As pointed out by Bommer (2006), the available empirical data are insufficient to provide reliable indications of the upper tails of associated probability distributions.

The largest ground particle velocity ever measured during an earthquake is 3.18 m/sec. Some approaches yield limits that are roughly consistent with this number, but others suggest some potential to exceed it. This article is intended more as a review and tutorial than an exhaustive research paper, but it does present some novel discussion on the insights that can be gained by considering ground motion during nuclear explosions.

2. Why is Ground Motion Important?

Simply put, large ground motions from earthquakes kill people and cause tremendous economic damage. The 1976 Tangshan earthquake in China killed over a quarter million people. The 10 deadliest earthquakes combined have killed nearly a million and a half people since 1900. The 10 most economically damaging earthquakes in history have caused approximately $1.37 trillion in damage (2012 dollars; Daniell et al. 2012). The 2011 Tohoku earthquake in Japan, which caused the Fukushima Daichi nuclear disaster, accounted for approximately $324 billion in damage all by itself. Approximately 70% of direct economic damage from earthquakes has been caused directly by ground shaking; the rest has been caused by tsunamis, fire, liquefaction, and landslides—all of which are ultimately induced by ground motion as well (Daniell et al. 2012).

3. Earthquake Intensity and Ground Motion

The amplitude of ground motion caused by an earthquake depends on the size of an earthquake, often expressed as magnitude but best measured by seismic moment; the distance to the earthquake source; and the geological structure in the area.

A. Traditional Intensity Scales

The interaction of the ground motion with humans and the built environment has historically been characterized by a semi-quantitative descriptive quantity known as the intensity of the earthquake. Several intensity scales are used in different parts of the world, including the Modified Mercalli scale favored in the United States, the Japan Meteorological Agency (JMA) scale, the European macroseismic scale in the European Union, the Medvedev-Sponheuer-Karnik (MSK) Scale in Russia, and the Liedu scale in China (Aptikaev et al. 2008). These scales all have levels designated as integers, with accompanying verbal descriptions of effects. As an example, the Modified Mercalli scale ranges from Level I, "Not felt," to Level XII, "Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air." The various scales differ in their levels and descriptors, but can be roughly mapped into one another. We emphasize that earthquake intensity is not the same as earthquake magnitude. A large earthquake far away, observed in a desolate area, will have low intensity, but a small earthquake close to a built-up area may have a much higher intensity.

B. Instrumental Intensity Scales with Reference to Ground Motion

Considerable work has been done to place intensity on a more rigorous quantitative footing, relating it to actual measured ground motion (Trifunac and Brady 1975; Wald et al. 1999; Worden et al. 2010, 2012, 2020). Figure 1 shows an example of one such motion-based intensity scale. This instance of the "Shakemap Intensity Scale" (Worden et al. 2012, 2020) has 10 levels, tied to ground velocity and acceleration. Ground accelerations greater than roughly 1.4 g or velocities exceeding roughly 1.8 m/sec are associated with very heavy damage. Both acceleration and velocity are important quantities expressing ground motion. Earthquake engineers have tended to emphasize acceleration, but it has been observed that velocity correlates better with observed damage (Erteleva 2016; Makris and Black 2004). Note that the velocity and acceleration numbers in an instrumental scale can vary depending on earthquake and region. The scale in Figure 1 can serve as a notional example for this discussion.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Figure 1. Example of an Instrumental Intensity Scale Linking Ground acceleration and Velocity to Observed Damage and Effects. From Worden et al. (2020); scale is based on Worden et al. (2012).

4. The Largest Ground Velocity Ever Measured in an Earthquake

The largest ground particle velocity ever recorded was 3.18 m/sec, during the 1999 Chi-Chi earthquake in Taiwan (Anderson 2008). Table 1 lists the top-13 recorded ground velocity measurements. Four of the top 13 were recorded during the Chi-Chi earthquake (Anderson 2008).

Table 1. Largest Recorded Ground Particle Velocities in Earthquakes. From Anderson (2008).

Rank	Earthquake	Date	Location	Moment Magnitude	Depth	Station	Peak Ground Velocity, m/sec
1	Chi-Chi	1999-09-20	Taiwan	7.6	33	TCU068	**3.18**
2	Chi-Chi	1999-09-20	Taiwan	7.6	33	TCU052	**2.00**
3	Kobe	1995-01-16	Japan	6.9	17.9	Takabri	**1.70**
4	Northridge	1994-01-17	U.S. (California)	6.7	17.5	Simi Valley	**1.60**
5	Kashiwazaki-Niigata	2007-07-16	Japan	6.6	10	NIG018 Kashiwazaki	**1.52**
6	Chi-Chi	1999-09-20	Taiwan	7.6	33	TCU065	**1.51**
7	Landers	1992-06-28	U.S. (California)	7.6	33	Lucerne	**1.47**
8	Niigata-Ken Chuetsu	2004-10-23	Japan	6.6	15.8	Kawaguchi	**1.45**
9	Cape Mendocino	1992-04-25	U.S. (California)	7.0	21	Cape Mendocino	**1.38**
10	Niigata-Ken Chuetsu	2004-10-23	Japan	6.6	15.8	NIG019 Ojiya	**1.37**
11	Northridge	1994-01-17	U.S. (California)	6.7	17.5	Sylmar Converter	**1.35**
12	Northridge	1994-01-17	U.S. (California)	6.7	17.5	Sylmar Converter	**1.32**
13	Chi-Chi	1999-09-20	Taiwan	7.6	33	CHY080	**1.26**

A. The Chi-Chi Earthquake

The Chi-Chi earthquake with a moment magnitude M_w of 7.6, occurred on 21 September 1999 in a densely populated area of central and western Taiwan. It involved a large thrust rupture along the Chelungpu thrust fault, manifesting at the surface as a break 100 km long. It produced fault scarps with displacements up to 8 m and created a waterfall on the Tachiahsi River (Figure 2; Lee and Chan 2007; Yue et al. 2005; Shin and Teng 2001). The earthquake killed 2,470 people, injured 11,305, and destroyed around 100,000 structures. Bridges collapsed, dams ruptured, landslides occurred, and lifelines were disrupted (Shin and Teng 2001).

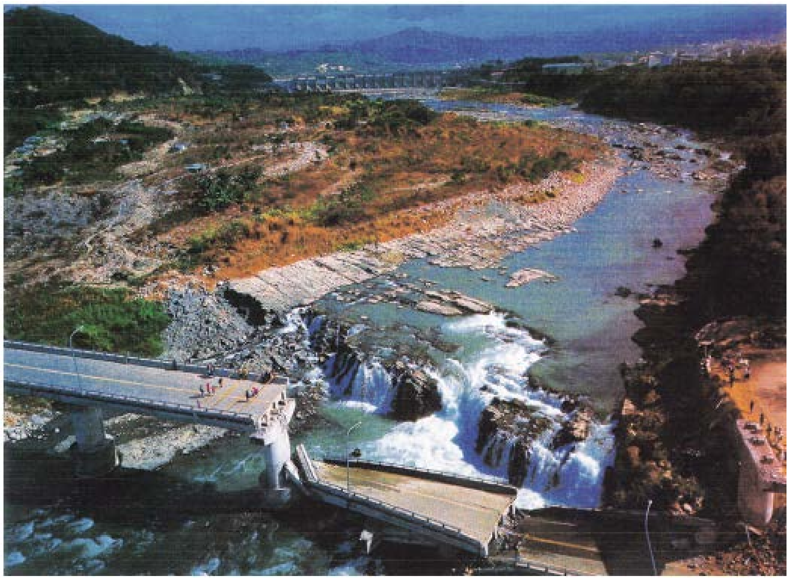

Figure 2. The Chi-Chi Earthquake of 1999 Creates a Waterfall on the Tachiahsi River in Taiwan. From Shin and Teng (2001).

Yet despite the scale of the destruction, the Chi-Chi earthquake was neither the largest nor the deadliest earthquake in recorded history. In the list of largest earthquakes, it places 233rd, and in the list of deadliest ones it is 75th (USGS 2020; see Table 2 and Table 3). In economic damage, it ranks higher. It is estimated to have caused the seventh-highest direct economic losses of any earthquake (Daniell et al. 2012; see Figure 3).

Table 2. Largest Earthquakes Since 1900

Rank	Year	Earthquake	Country	Moment Magnitude
1	1960	Bio-Bio	Chile	9.5
2	1964	Alaska	U.S. (Alaska)	9.2
3	2011	Tohoku	Japan	9.1
4	2004	Sumatra	Indonesia	9.1
5	1952	Kamchatka	Russia	9.0
6	1906	Ecuador	Ecuador	8.8
7	2010	Bio-Bio	Chile	8.8
8	1965	Rat Islands	U.S. (Alaska)	8.7
9	2012	Sumatra	Indonesia	8.6
10	1946	Alaska	U.S. (Alaska)	8.6
…	…	…	…	…
233	1999	Chi-Chi	Taiwan	7.6

Source: Data from USGS (2020).

Table 3. Deadliest Earthquakes Since 1900

Rank	Year	Earthquake	Country	Moment Magnitude	Fatalities
1	1976	Tangshan	China	7.5	255,000
2	2004	Sumatra	Indonesia	9.1	227,898
3	2010	Haiti	Haiti	7.0	222,521
4	1920	Haiyuan, Ningxia	China	7.8	200,000
5	1923	Kanto	Japan	7.9	142,800
6	1948	Ashgabat	Turkmenistan	7.3	110,000
7	2008	Eastern Sichuan	China	7.9	87,857
8	2005	Pakistan	Pakistan	7.6	86,000
9	1908	Messina	Italy	7.2	72,000
10	1970	Chimbote	Peru	7.9	70,000
…	…	…	…	…	…
75	1999	Chi-Chi	Taiwan	7.6	2,470

Source: Data from USGS (2020); magnitude is moment magnitude.

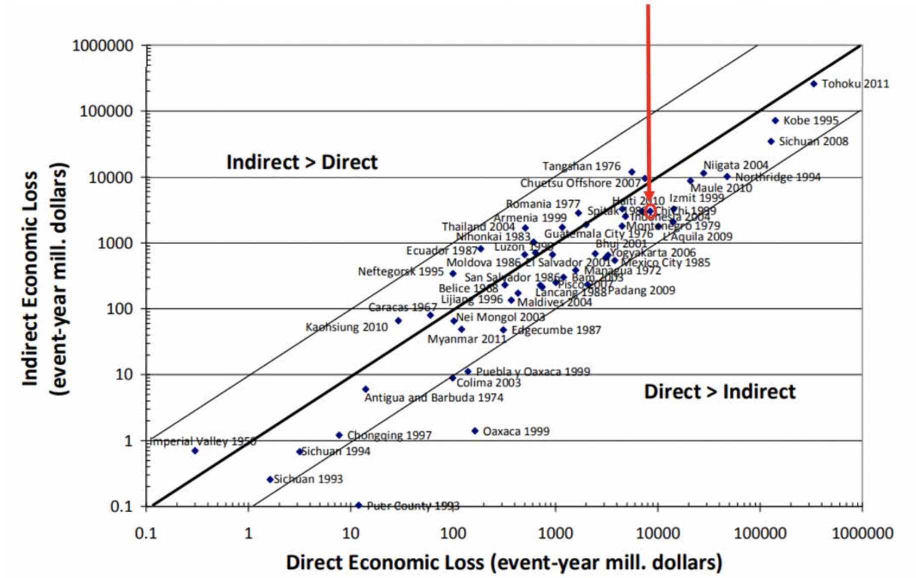

Figure 3. Direct and Indirect Economic Losses from Earthquakes, with the Chi-Chi Earthquake Indicated. Adapted from Daniell et al. (2012)

B. Why Chi-Chi? Location, Location, Location!

Why then was Chi-Chi the earthquake the one with the highest recorded ground velocity? The main reason is that instruments happened to be operative in the right place at the right time. Figure 4 shows the location of the instrument that recorded the largest velocity. It was extremely close to the surface rupture of the Chelungpu fault, on the hanging wall. The location experienced relatively unconstrained heaving block motion. Velocities on the footwall, directly across the fault surface, were considerably lower, with a maximum of 1.15 m/sec (Chen et al. 2001).

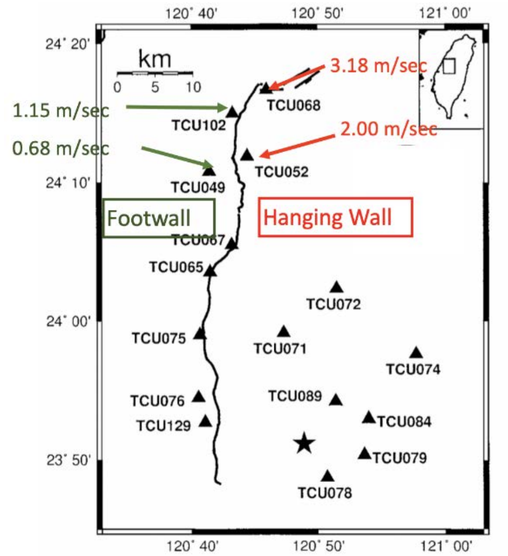

Figure 4. Locations of Instruments That Recorded High Ground Velocities near the Chelungpu Fault in Taiwan during the Chi-Chi Earthquake of 1999. Adapted from Chen et al. (2001).

5. Probabilistic Assessment of Maximum Ground Motion

One approach to estimating the maximum possible ground motion is to use probabilistic seismic hazard analysis. A notable application of the technique was to evaluate the risk associated with storing nuclear waste at a proposed depository in Yucca Mountain in the U.S. state of Nevada. The waste would potentially be stored 600 m underground, 300 m above the water table, in a geological environment dominated by thick sequences of tuffs. Although such a location might be thought quite safe, the problem is that Yucca Mountain is in the tectonically active Basin and Range geologic province, and the site is surrounded by active normal faults.

Because of the geologically active nature of the site, the Nuclear Regulatory Commission (NRC) required assessment of seismic hazard, and placed some very stringent requirements on the analysis. The NRC required an estimate of ground motions with one chance in 10,000 of being exceeded in 10,000 years, that is, with annual exceedance probability of 1×10^{-8} (Hanks et al. 2006). Hanks (2006) and Wong (2006) summarize some probabilistic seismic hazard analyses performed by various investigators. These found that the site could experience ground motions of about 3.5 m/sec with annual exceedance probability of 1×10^{-6}, ~7 m/sec with an annual exceedance probability of 1×10^{-7}, and 13 m/sec with an annual exceedance probability of 1×10^{-8}. These are extremely high velocities, given what is known about the structural geology of the region and its tectonic history. Nevada is a seismogenic zone, but has never been thought to be capable of producing great earthquakes to the same extent as places like Chile, Japan, or Alaska. This has led some observers to worry that the estimates are dominated by the tail end of a lognormal distribution and are not realistic (Reiter 2006). Deterministic calculations for the site by Andrews et al. (2007), using paleo-seismological estimates of previous fault slippage, yielded a much lower estimate of 3.6 m/sec for the maximum possible ground motion around Yucca Mountain.

6. Physical Approaches to Understanding the Maximum Possible Ground Velocity

A. Laboratory Rock Fracture

Let us naively consider laboratory fracture of an intact rock specimen, say granite. At the point of fracture, a wide range of strain ε has been observed. Consider the range of strain from 10^{-3} to 10^{-2}, consistent with measurements in Goldsmith et al. (1976). Particle velocity u_p is related to wave velocity u_{wave} and strain via the equation

$$u_p = u_{\mathrm{wave}}\varepsilon \, .$$

For u_{wave} ~ 6 km/sec, typical for granite, u_p ranges from ~6 m/sec to ~60 m/sec. This is a gross upper limit—almost certainly too high to be a useful guideline. The problem is that a fault rupture in the real Earth does not involve the controlled fracture of an intact specimen. It is a complex process at a much larger scale, involving huge, heterogeneous, jointed and faulted rock masses with in-situ properties differing significantly from those of an intact specimen. These masses stick-slip past each other, generally on a preexisting fault surface.

B. Brune's Approach: Available Stress for Fault Slip

The U.S. geophysicist James Brune (1970) considered a simple analytic model of a planar, infinite fault. As a tangential stress is applied, the two sides slip past each other, all at once. This generates a shear-wave pulse. Brune derived simple expression for particle velocity

$$u_p = (\sigma/\mu)u_{\mathrm{wave}} \, .$$

The critical parameter is σ, the effective stress available for fault rupture. Brune used a reasonable estimate for σ of 100 bars (Heidbach et al. 2010). This yields u_p ~1 m/sec. Brune's analysis suggests a maximum possible ground velocity of order 1 m/sec, or some small multiple thereof.

C. Ida's Approach: Crack Propagation

The Japanese physicist Yoshiaki Ida (1973) considered stress concentration at the tip of a propagating rupture, with particle velocity roughly given by

$$u_p \sim (\sigma_0/\mu)c \, ,$$

where *c* is the rupture velocity, estimated at ~1 km/sec, μ is the shear modulus, and σ_0 is the cohesive stress keeping the material intact, working against the rupture at the crack tip. For cohesion governed by interatomic interactions, σ_0 *is* roughly equal to the shear modulus μ, implying a particle u_p of the same order as the rupture velocity, or ~ 1 km/sec—three orders of magnitude larger than the largest ground velocity recorded in an earthquake. But for cohesion governed by the gross strength of a bulk rock mass in the field, σ_0 is closer to 1 kbar. Using a typical value of 200 kbar for the shear modulus of granite (Pariseau 2011), we obtain a value of u_p closer to around 5 m/sec.

D. Detailed Strong-Motion Seismological Studies of Fault Slip

Over the years, strong-motion seismologists have developed detailed models of fault rupture to explain seismic measurements in the vicinity of earthquakes. McGarr and Fetcher (2007) compiled many of these studies. A simplified extract from their paper appears in Table 4. Inferred slip rates along faults range from around 3.6 to 12 m/sec. The particle velocity near a slipping fault is about half the slip rate, so maximum ground velocities range between 1.8 and 6 m/sec. The inferred maximum ground velocity of 2.85 m/sec for the Chi-Chi earthquake is fairly close to the maximum measured value of 3.18 m/sec.

Table 4. Inferred Slip Rates from Earthquakes Modeled by Various Investigators (from the compilation of McGarr and Fletcher 2007).

Year	Earthquake	Country	Moment Magnitude	Inferred Fault Slip Rate, m/sec	Inferred Maximum Ground Velocity, m/sec
1979	Imperial Valley	U.S. (California)	6.4	3.64	1.82
1995	Kobe	Japan	6.9	3.64	1.82
1989	Loma Prieta	U.S. (California)	7.0	7.58	3.79
1989	Loma Prieta	U.S. (California)	7.0	8.65	4.33
1992	Landers	U.S. (California)	7.2	5.90	2.95
1999	Hector Mine	U.S. (California)	7.2	2.28	1.14
1994	Northridge	U.S. (California)	6.7	8.95	4.48
1999	Izmit	Turkey	7.6	12.00	6.00
1999	Chi-Chi	Taiwan	7.6	5.70	2.85

E. Combining with Laboratory Studies

McGarr and Fletcher (2007) also considered the earthquake-slip studies together with experimental studies of blocks of rock slipping past each other in a laboratory setting. In this way they could infer the behavior of peak slip rate for events ranging in size over several orders of magnitude. The results show that peak slip rates do not scale with event size, suggesting a physical limit—although there is considerable scatter in the data, as shown in Figure 5. Their inferred limits on peak ground velocity using this expanded analysis are in the range of 2.5 to 3 m/sec, which is close to the maximum recorded during the Chi-Chi earthquake.

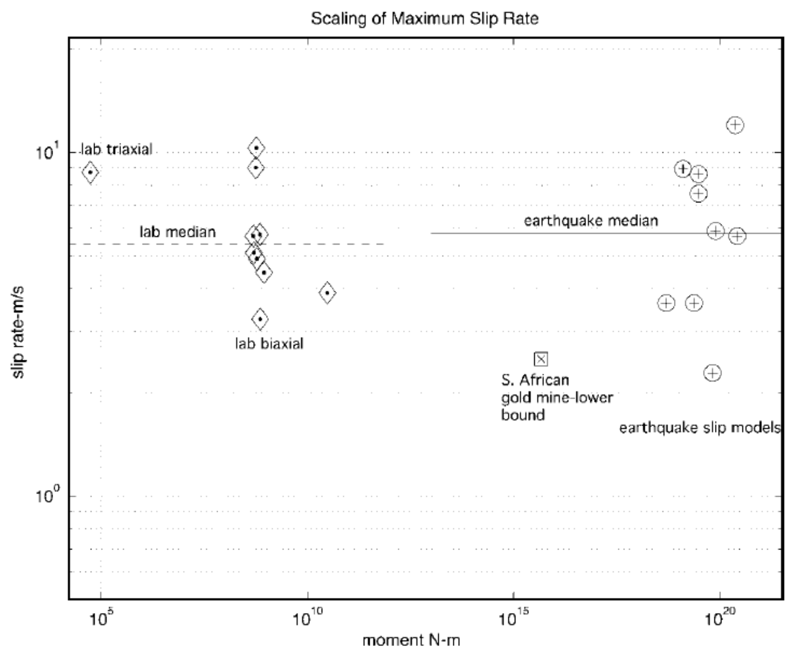

Figure 5. Peak Slip Rates Estimated for Various Earthquakes and Laboratory Stick-Slip Events. Maximum particle velocity is half of slip rate. From McGarr and Fletcher (2007).

7. Can Nuclear Explosions Provide Insight?

Underground nuclear explosions, which represent a significant external input of energy into the ground, have produced ground-particle velocities as high as 80 m/sec at close ranges in the nonlinear deformation zone (see Section 7.C), values over 25 times the highest velocity ever observed as a result of an earthquake. It is possible that nuclear explosions may provide some input into the upper limits of a naturally occurring ground-particle velocity.

A. Size of Nuclear Explosions

The size of a nuclear explosion is expressed in equivalent tons of the chemical explosive trinitrotoluene (TNT). A standard kiloton (kt) of TNT is equal to 4.2×10^{12} joules. Underground explosions conducted by the United States have ranged in size from fractions of a kiloton to several megatons (Mt). There are important differences between nuclear explosions and earthquakes in terms of the frequency content and radiation pattern of produced seismic waves, but—very roughly—a 1 kT explosion observed at teleseismic distances looks like an earthquake of body wave magnitude 4.45. A 1 Mt explosion looks roughly like an earthquake of body wave magnitude 6.7.

B. Cube-Root Yield Scaling

In the analysis of nuclear explosion ground shock, it is useful to compare data from different explosions of widely varying yields. Having a way to normalize this wide range in yield would be convenient. The scaling factor used is based on the cube root of the yield (Mueller and Murphy 1971; Denny and Johnson 1991). This arises from simple dimensional considerations of energy and volume.

The volume of the fireball associated with an atmospheric nuclear explosion or the vaporized zone in rock associated with an underground explosion is proportional to the energy of the explosion. In a uniform medium the yield varies as length cubed, or, alternatively, length or distance can be viewed as varying with the cube root of yield. Normalizing distances thus entails dividing by cube root of yield. Considering the dimensions of specific energy $(\text{length/time})^2$ suggests that time of fireball and cavity growth should also vary as the cube root of yield. Ground-particle velocity at a given scaled distance should be invariant with yield, while we would normalize acceleration by multiplying by cube root of yield and normalize displacement by dividing. These scaling relationships are useful and commonly applied, even though they necessarily represent an oversimplification. As Denny and Johnson (1991) point out, care must be taken in scaling ground-motion data recorded by different types of instruments having varying frequency responses.

C. Deformation Regimes

Close to the source, pressures are high enough that the rock behaves hydrodynamically, suffering the passage of a strong shock wave. The rock behaves according to its superadiabatic Hugoniot equation of state. It behaves essentially as a compressible fluid, and solid strength effects are unimportant. As pressures drop, the ground motion becomes nonlinearly anelastic or plastic, and variables such as strength and porosity become important. This regime continues until the "elastic radius" is reached, as shown schematically in Figure 6. From very far away, the nuclear explosion appears to be a source encapsulated within this elastic radius, radiating seismic elastic waves. In the area closer to the source, the "elastic radius" is really a more gradual transition zone between nonlinear and linear behavior.

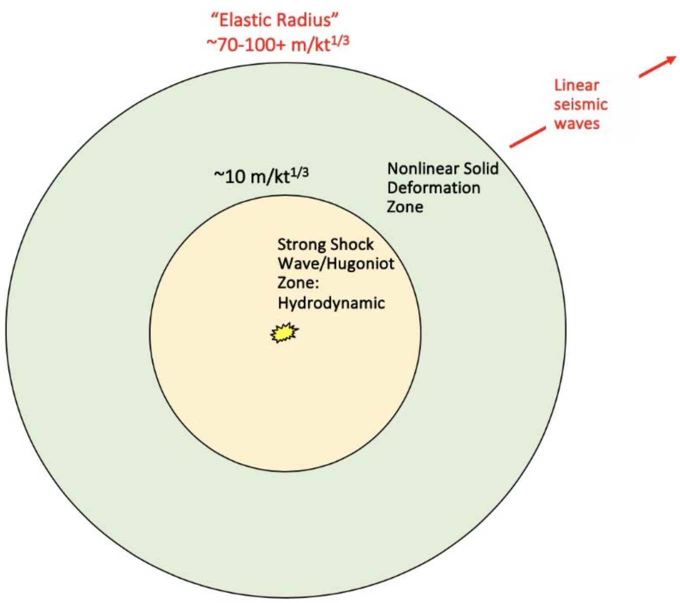

Figure 6. Deformation Regimes in the Vicinity of an Underground Nuclear Explosion

1. Transition from Hydrodynamic Behavior to Nonlinear Plastic Deformation

Perret and Bass (1975) analyzed data from U.S. underground explosions and determined the rough scaled distances at which transition occurs between the different deformation regimes. The transition between hydrodynamic and nonlinear plastic deformation manifests itself as an inflection in the variation of pressure with scaled distance. At pressures greater than 10–20 kbar, the regime is hydrodynamic, and pressure varies nearly as the inverse cube of scaled range. In the nonlinear solid-deformation regime, pressure varies nearly as the inverse square. Data presented by Perret and Bass suggest that the transition between the hydrodynamic and nonlinear regimes occurs at scaled ranges of roughly 10 m/kt$^{1/3}$.

2. Transition from Nonlinear Deformation to Linear Elasticity

Perret and Bass (1975) found that the transition from nonlinear plastic deformation to linear elasticity manifests itself as an inflection in the variation of scaled acceleration with scaled range. For alluvium this transition occurs at scaled ranges of roughly 70 m/kt$^{1/3}$, but for tuff and granite it appears to occur at scaled ranges of around 80 to 100 m/kt$^{1/3}$. We emphasize that these are far from precise quantities. Note that estimates of scaled elastic radius by various investigators range from ~70 to ~500 m/kt$^{1/3}$ (e.g., Perret and Bass 1975, 56, 57; Denny and Johnson, 1991, 9; see also Foxall 2006 for additional discussion of the nonlinear-to-linear transition).

3. Particle Velocities in the Various Deformation Regimes

Figure 7 shows peak ground-particle velocity for underground nuclear tests in granite versus scaled distance, with the rough extent of each deformation regime indicated. In the hydrodynamic regime, subject to a strong shock wave, particle velocities reach kilometers per second. In the nonlinear regime they range from meters to tens of meters per second. In the elastic regime they are well under 10 m/sec. Around the transition zone they range from about 2 to 12 m/sec.

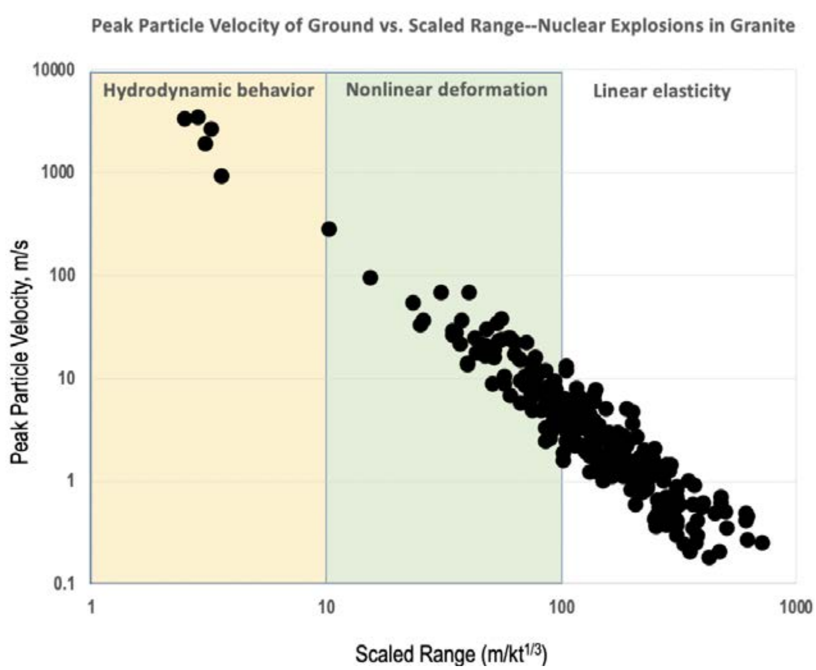

Figure 7. Peak Ground Particle Velocity for Underground Nuclear Explosions in Granite. Data from Perret and Bass (1975) and Xu et al. (2014).

4. Particle Velocity at the Onset of Nonlinear Deformation: A Nuclear-Inspired Limit?

In a nuclear explosion, external energy is applied to the ground that can breach the rock's Hugoniot elastic limit and make it behave essentially as a compressible fluid. An earthquake cannot supply such energy. The tectonic stresses that accumulate and eventually cause the earthquake are at least partly relieved by the earthquake itself. They do not keep building up. Although there may indeed be some plastic deformation and nonlinear behavior close to the fault, the causative stresses are relieved and do not continue to increase and drive the rock all the way through its nonlinear deformation regime and into the Hugoniot. It seems reasonable to suppose, then, that the ground-particle velocity around the transition between roughly linear elastic behavior and nonlinear deformation may represent the limit of possible ground motion, at least for shallow earthquakes.

What are the particle velocities near the transition? The data and analysis of Perret and Bass (1975) suggest that for alluvium, particle velocity is roughly 1.8 m/sec; for tuff, around 2 m/sec; and for granite, around 6–10 m/sec. The figure for granite suggests that someday an instrument in the right place for the right earthquake could measure a ground velocity considerably higher than the current maximum.

8. Summary of Possible Limits to Ground Velocity

Table 5 shows the inferred limits for the maximum ground-particle velocity in a shallow earthquake. Many of the numbers are roughly consistent with the maximum observed measurement of 3.18 m/sec, recorded in the 1999 Chi-Chi earthquake. The one obtained by probabilistic seismic hazard analysis for Yucca Mountain is considerably higher, and a different probabilistic analysis with different inputs could produce a number that is higher still. Examination of the transition from linear to nonlinear behavior in the vicinity of nuclear explosions produces some guesses lower than the current measured maximum, and some higher. Taken together, the estimates suggest that the physical limit on the maximum ground velocity may indeed be higher than the largest measurement to date, perhaps as high as 10 m/sec, but more likely in the range of 5–6 m/sec.

Table 5. Inferred Upper Limit of Ground Particle Velocity in an Earthquake, Using Various Methods

Method	Inferred Upper Limit of ground particle velocity, m/sec
Actual largest field measurement	3.18
Probabilistic seismic hazard analysis	13+
Available stress for fault slip	~1 or small multiple
Crack propagation	~5
Fault slip inferred in several strong earthquakes	~2 - 6
Fault slip inferred in several strong earthquakes combined with laboratory slip measurements	~2.5 - 3
Insight from nuclear explosions (alluvium)	~1.8
Insight from nuclear explosions (tuff)	~2
Insight from nuclear explosions (granite)	~6-10

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14. ABSTRACT
This article discusses approaches to determining the largest possible ground motion during an earthquake occurring near Earth's surface. The problem is a difficult one because the available empirical data are insufficient to provide reliable indications of the upper tails of associated probability distributions. The largest ground-particle velocity ever measured during an earthquake is 3.18 m/sec. Some approaches yield limits that are roughly consistent with this number, but others suggest some potential to exceed it. We suggest that the highest particle velocity near the transition to elasticity indicates the maximum ground velocity possible in a shallow earthquake. Considering data observed in granite, that transition takes place at a scaled range from the explosion source where particle velocity is about 6–10 m/sec—suggesting that the current maximum velocity measurement may not represent an absolute physical limit, but rather a limitation in sampling.

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