Lower Bounds on Ground Motion at Point Reyes During the 1906 San Francisco Earthquake from Train Toppling Analysis

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Abstract

Independent constraints on the ground motions experienced at Point Reyes station during the 1906 San Francisco earthquake are obtained by analyzing the dynamic response of a train which overturned during the earthquake. From this analysis, we conclude that the PGA and PGV at Point Reyes station would have been at least $4\ \mathrm{m/s^2}$ and $0.5\ \mathrm{m/s}$, respectively. This lower bound is then used to perform simple checks on the synthetic ground motion simulations of the 1906 San Francisco earthquake by Aagaard et al. [1]. It is also shown that the hypocenter of the earthquake should be to the south of Point Reyes station for the overturning of the train to match the description provided by Jordan [7].

Introduction

The 18th April, 1906 San Francisco earthquake (M_w 7.8) and the subsequent investigation of this earthquake [8] marked the birth of modern earthquake science in the United States. The nearest ground motion from this earthquake was recorded at Mount Hamilton by a three-component pendulum. From this recorded ground motion, Boore [4] and Lomax [9] constrained the hypocenter of this earthquake to lie offshore from San Francisco. Recently efforts have also been made to recreate the strong ground motion from this earthquake using the limited available data about the slip distribution [1, 12]. Due to the lack of sufficient data, there is still some uncertainty in the location of the epicenter and the near source ground motions from this earthquake.

In this paper, we analyze a train that overturned near Point Reyes station during the 1906 San Francisco earthquake to obtain independent constraints on the ground motions experienced at this location. As per Jordan's description [7] of the incident, the train which was initially stationary, lurched to the east, followed by another lurch to the west which threw the train on its side. An image of the overturned train is shown in Fig. 1 and a map with the train location (black circle) in relation to the San Andreas fault (red line) is shown in Fig. 2(a). Estimating the ground motion parameters and the direction of the ground motion pulse required to overturn the train as described by Jordan [7] can supplement the limited available data about this earthquake.

To estimate the ground motion required to overturn the train, Anooshehpoor et al. [3] approximated the train to a rigid rectangular block [Fig. 2(b)] and the fault-normal acceleration to a full sinusoidal pulse and analytically estimated the minimum sine wave required to overturn the train model as described by Jordan [7]. Since a sinusoidal wave does not capture all the features of an actual earthquake ground motion, they also conducted numerical analysis using scaled records of two accelerograms and estimated the minimum scaling factor required to overturn the train in each case. They used accelerograms recorded at Lucerne station during the 1992 Landers earthquake and a synthetic accelerogram generated at Point Reyes station for a M_w 8 earthquake rupturing northwest along the San Andreas fault with epicenter near the Golden Gate bridge. This analysis conducted by Anooshehpoor et al. [3] does not include the effects of vertical ground motion and considers very limited set of earthquakes. Here, we extend this analysis by analyzing

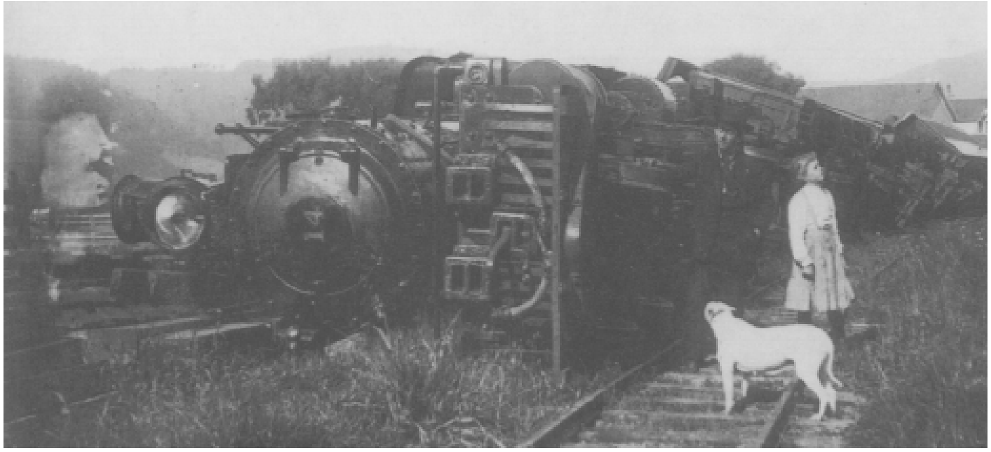


Figure 1: San Francisco bound train which overturned at Point Reyes Station during the 1906 San Francisco earthquake [3].

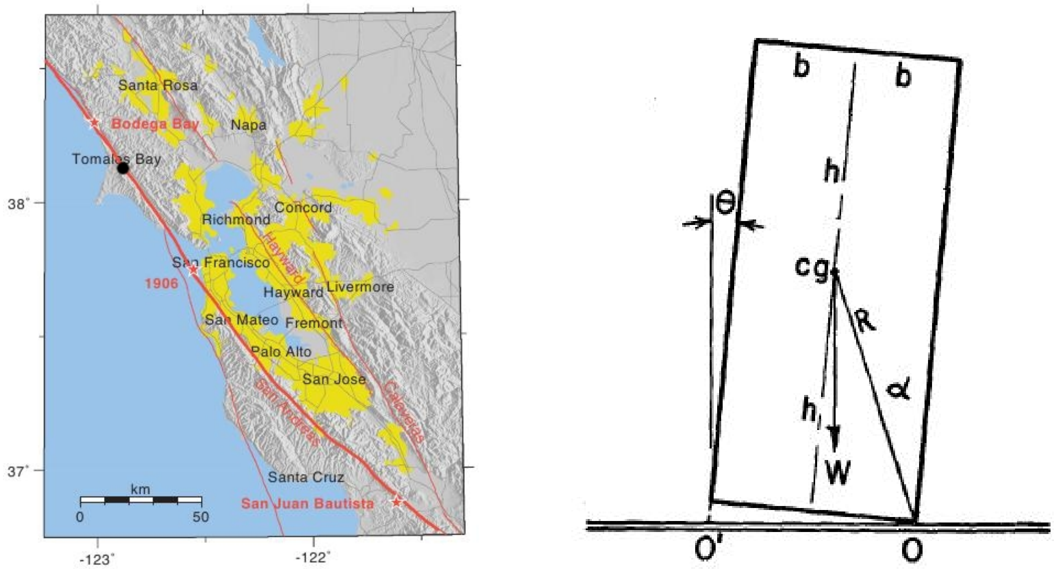
the rectangular train model under both vertical as well as horizontal ground motions from 140 worldwide earthquakes to obtain the overturning fragility of the train as a function of ground motion parameters. We also analyze the train model under the ground motions at Point Reyes station from the 1906 like earthquake simulations by Aagaard et al. [1] starting at three different hypocenter locations [indicated by the red stars in Fig. 2(a)] to arrive at independent constraints on the possible hypocenter location of the 1906 San Francisco earthquake.

Overturning fragility of the train

The locomotive of the overturned train was the narrow gauge engine number 14, built in 1891 by Brooks and scrapped in 1935 [5]. Anooshehpoor et al. [3] approximated the train sitting on the rails to a very long rectangular block with height and width of 3.76 m and 0.91 m, respectively, sitting on a rigid horizontal ground. This idealized rectangular train model is assumed to come in contact with the ground at only the two corners O and O', which is analogous to the train wheels coming in contact with the rails. Any impact between the train model and ground, i.e, when the point of rotation changes from O to O' or vice versa, is assumed to inelastic in nature. Since the wheels of the train are guided by the rails, the train model cannot slide on the ground. So, we use a high static and kinetic coefficient of friction of 1.2 between the train model and the ground. We also assume that the suspension system installed in the train was sufficiently stiff for the train to behave like a rigid body. Thus the rocking response of a stationary train under earthquake excitation can be idealized with that of a long rigid rectangular block.

There have been numerous analytical, numerical and experimental studies on the rocking response of a rectangular block under ground excitation [6, 10, 14, 15]. In this paper, we use a rigid body dynamics algorithm [13] to analyze the rocking response of the train model under earthquake excitation. This algorithm has been validated against analytical solution for the rocking response of a rectangular block. For this analysis, we consider ground motions from 140 worldwide earthquakes with magnitude greater than 6 and distance from rupture site less than 100 km (see [11] for the list of earthquakes). These ground motions are first normalized such that the peak ground acceleration (PGA) of the dominant ground motion component is $1\ \mathrm{m/s^2}$. These normalized ground motions are then scaled from PGA of $1\ \mathrm{m/s^2}$ to $19\ \mathrm{m/s^2}$ in steps of $1\ \mathrm{m/s^2}$. Since the PGA of the ground motions are scaled linearly, the peak ground displacement (PGD) and peak ground velocity (PGV) also scale linearly with the same scaling factor as the PGA.

The rectangular train model is analyzed under each of these scaled ground motions. The dominant horizontal ground motion is applied along the width of the train model and the vertical ground motion is



(a) (b)

Figure 2: (a) A map showing the San Andreas fault (red line) and Point Reyes Station (black circle). The red stars indicate the different hypocenter locations for the 1906 San Francisco like earthquake simulation with the one off the coast of San Francisco being the currently accepted hypocenter location [1]; and (b) rectangular block model of the train [6].

applied along its height. Since the train model is very long, the rocking response of the train model is restricted to its cross-section as shown in Fig. 2(b). Therefore, the non-dominant horizontal ground motion applied along its length does not influence the response of the train model. From the set of scaled ground motions, the subset of ground motions for which train overturns is represented by the red squares in the PGD vs PGA and PGV vs PGA space as shown in Figs. 3(a) and 3(b), respectively. There is no data available in the region to the left of the black line in these figures as the accelerograms are scaled linearly only along PGA. It can be seen from these figures that the train does not overturn unless the PGA of the ground motion is at least $4\ \mathrm{m/s^2}$. Also, the minimum PGD required to overturn the train model is around $0.1\ \mathrm{m}$ [Fig. 3(a)]. On the other hand, the minimum PGV required to overturn the train model is approximately $0.5\ \mathrm{m/s}$ for PGA between $4 - 11\ \mathrm{m/s^2}$ and then it linearly increases with PGA and results in a minimum PGV of $1.2\ \mathrm{m/s}$ at PGA of $19\ \mathrm{m/s^2}$. Therefore, the minimum PGA, PGD and PGV required to overturn the train model are $4\ \mathrm{m/s^2}$, $0.1\ \mathrm{m}$ and $0.5\ \mathrm{m/s}$, respectively. This lower bound, however, does not imply that all ground motions with parameters greater those given above will overturn the train model.

This lower bound can be used to perform a simple check on the synthetic ground motion simulations of the 1906 San Francisco earthquake by Aagaard et al. [1]. From their simulations, the ground motion at Point Reyes station (station SF432) in the east-west direction have a PGA between $4.5 - 6\ \mathrm{m/s^2}$, PGV between $0.8 - 1.6\ \mathrm{m/s}$ and PGD approximately $1\ \mathrm{m}$. These values are above the lower bound and therefore there is a non-zero overturning probability of the train model for these ground motions.

Inferences on the hypocenter location

In this section, we obtain independent constraints on the hypocenter of the 1906 San Francisco earthquake without using the ground motions recorded at Mount Hamilton. For this analysis, we use three different 1906 like earthquake simulations developed Aagaard et al. [1] starting at Bodega Bay, San Francisco and

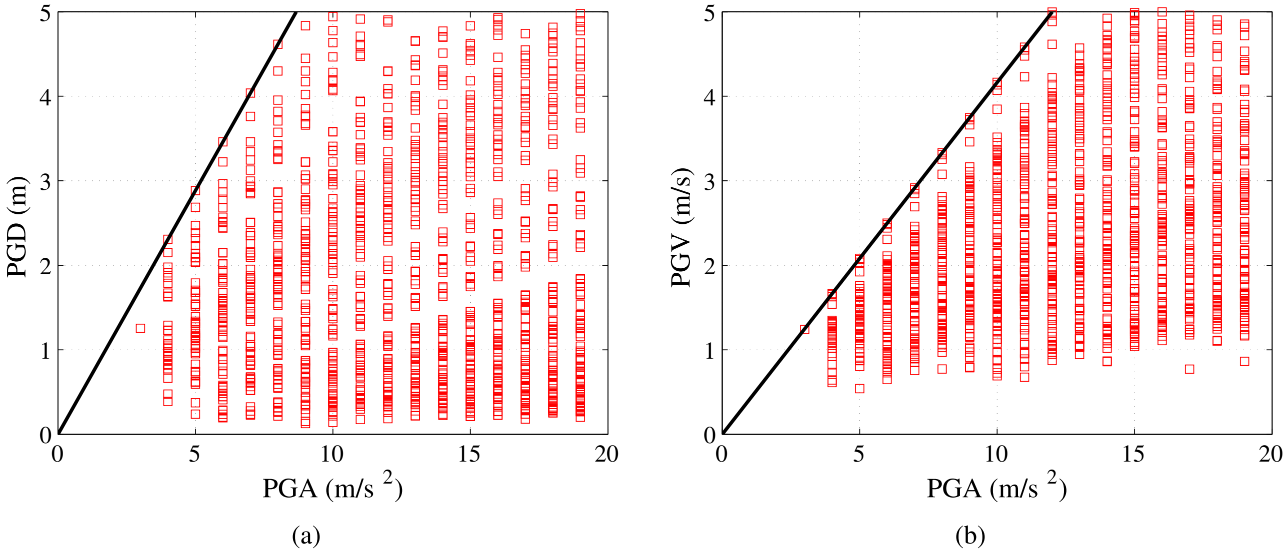


Figure 3: Overturning of the train model indicated by the red squares as a function of (a) PGD vs PGA and (b) PGV vs PGA. There is no data available to the left of the black line in these figures due to the ground motions being scaled linearly in PGA. The minimum PGA, PGD and PGV required to overturn the train model are $4\ \mathrm{m/s^2}$, $0.1\ \mathrm{m}$ and $0.5\ \mathrm{m/s}$, respectively.

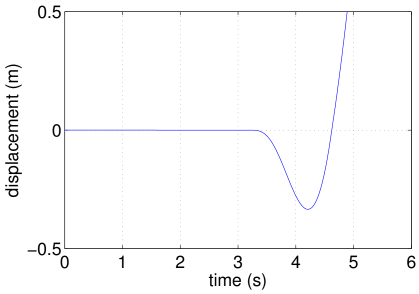
San Juan Bautista [Fig. 2(a)]. These ground motions simulations were obtained by combining the source model developed by Song et al. [12] with the recently constructed 3D geologic and seismic velocity models. The three simulations considered have the same slip distribution, rupture the same extent of the northern San Andreas fault but originate at different locations. The velocity time histories at the Point Reyes Station (station SF432) are extracted from these simulations (refer [2] for the time histories at different stations).

The train model is analyzed under each of these velocity time histories. The horizontal displacement time history of the center of mass of the train model with respect to the ground is given in Figs. 4(a), 4(b) and 4(c) for ground motion simulations starting at Bodega Bay, San Francisco and San Juan Bautista, respectively. Positive displacement corresponds to displacement of the train to the east. As can be seen from these figures, when the earthquake hypocenter is to the south of Point Reyes station, the train first lurches to the east and then overturns in the west, which matches with Jordan's description of the incident. Therefore, from our analysis the hypocenter of the 1906 earthquake should be to the south of Point Reyes station. This inference does not conflict with the currently accepted hypocenter location near San Francisco [9].

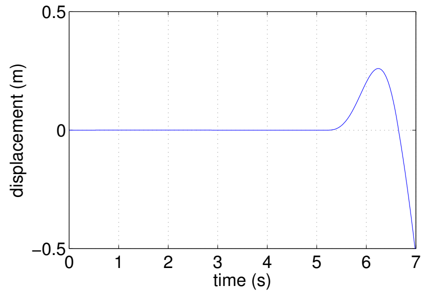
Conclusion

A train overturned at Point Reyes station during the 1906 San Francisco earthquake. In this paper, lower bounds on the ground motion experienced at the Point Reyes station during this earthquake are obtained by estimating the ground motion parameters required to overturn this train. The minimum PGA and PGV required to overturn the train are $4\ \mathrm{m/s^2}$ and $0.5\ \mathrm{m/s}$. This is used to perform a sanity check on the ground motion at this location from the synthetic ground motion simulations of the 1906 earthquake by Aagaard et al. [1].

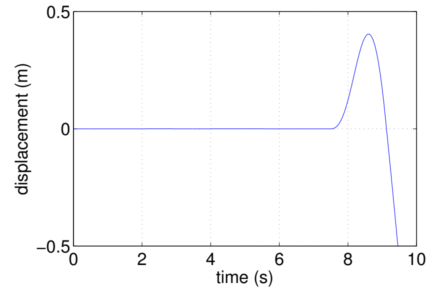
An independent constraint on the hypocenter location of the 1906 earthquake, which does not dependent directly on the recorded ground motion at Mount Hamilton, is also obtained by analyzing the train model under three different scenarios of the 1906 earthquake with hypocenter locations at Bodega Bay, offshore from San Francisco and San Juan Bautista. Our analysis suggests that for the train to overturn as per the description provided by Jordan [7], the hypocenter of the earthquake has to be to the south of Point Reyes



(a)



(b)



(c)

Figure 4: Horizontal displacement time history of the center of mass of the train with respect to the ground for ground motion at Point Reyes station from the three synthetic ground motion simulations of the 1906 earthquake obtained by Aagaard et al. [1] with hypocenter of the earthquake located at (a) Bodega Bay, (b) offshore from San Francisco and (c) San Juan Bautista. Positive displacement implies the movement of the train is towards east.

station. This agrees with the maximum-likelihood hypocenter location near San Francisco obtained by Lomax [9].

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