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Dynamic effects of surface fault rupture interaction with structures

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ABSTRACT

Surface fault rupture has caused significant damage to structures in several earthquakes. The propagation of the bedrock fault rupture through the overlying soil deposit has been studied by several researchers; however, the effects of fault rupture dynamics, as opposed to pseudostatic fault movement, have not yet been evaluated. There is the potential for dynamic effects to influence significantly structural damage due to the rapid rate of deformation imposed by surface fault rupture. Numerical simulations are performed to analyze the effects of the rate of fault rupture on dip-slip surface fault rupture for free-field and soil-structure interaction conditions. The numerical results indicate that in some limited scenarios, fault rupture dynamics can influence the amount of structural damage expected for a structure located near a fault. However, in most scenarios, fault rupture dynamics is expected to play a secondary role compared to fault, soil, and structural characteristics in evaluating building performance.

1. Introduction

Field observations confirm that structures within an earthquake surface fault rupture zone can significantly affect the way in which the fault rupture propagates through soil [1–4]. For example, the 15-story Banco Central building significantly diverted the surface expression of fault rupture around its buried bank vault, which limited damage to its structural system [1]. Laboratory experiments and numerical simulations have been conducted to analyze fault rupture diversion around structures [5–7]. Among these, geotechnical centrifuge experiments conducted by Bransby et al. [5,6] showed evidence that increasing the weight of a structure placed near a reverse fault caused increasingly greater diversion of the fault around the structure, while Anastasopoulos et al. [7] found that pseudostatic numerical simulations indicate that there are cases where structures significantly diverted fault rupture.

Only pseudostatic analyses of earthquake fault rupture propagation through soil and its interaction with overlying structures have been performed. The bedrock fault displacement has been imposed without consideration of the rate of the applied fault displacement, and therefore any potentially important dynamic effects have been ignored. However, fault rupture displacement occurs rapidly during an earthquake. Previous studies indicate that the average velocity of the ground surface during fault displacement, which is commonly referred to as fling-step, is on the order of 0.5–1.0 m/s [8–10]. There are even higher slip velocities determined from dynamic simulations although those calculations are commonly performed for linear-elastic rheology. Thus, dynamic effects could be significant, and these effects should be investigated. Addressing the effects of a dynamically applied permanent fault offset will provide a more complete understanding of soil-structure interaction effects and the role that the rate of rupturing may play in building performance during a surface fault rupture event. With many constructed facilities existing along the surface trace of active faults [11–14] and with regulators currently assessing the future of construction practices in fault zones [15], there is a pressing need to assess the potential significance of dynamic effects, because these effects have not been investigated. This is the primary aim of this paper.

In this paper, the effects of the rate at which a fault ruptures are investigated. The potential effects of the inertia of the soil and the overlying structure are considered. Rate effects on soil response are not be considered for the cases examined which all include dry sand. Furthermore, the transient part of the earthquake ground motion (i.e., due to vibratory shaking) is not included. Transient ground shaking will also occur coincident with permanent fault offset; however, the focus of these analyses is to calculate the expected permanent ground deformation taking into account

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dynamic soil-structure interaction rather than to calculate the total structural loads from a combination of fault offset and strong shaking. Structural loads from strong shaking can be added to the structural demands from permanent ground deformation using approaches similar to those described in Goel and Chopra [16,17]. This paper advances understanding by numerically evaluating the effects of fault rupture rate on fault rupture propagation through soil in the vicinity of structures for a variety of structural and soil conditions.

2. Previous work

The effects of dynamic free-field fault rupture through soil without structures were examined through some limited geotechnical centrifuge testing conducted by Roth et al. [18] and Scott [19]. For the dynamic centrifuge tests, a peak ground acceleration of approximately 0.5 g was applied. Transient ground shaking was not considered in these tests. Rather, they considered only the rate at which the fault rupture was applied. Both loose and dense sands were tested and compared to tests in which the base fault movement was applied pseudostatically. Unfortunately, the test setup required that the fault movement was applied on the footwall side of the reverse fault rather than the hanging wall side of the reverse fault as expected for the field case. A downward base displacement was applied to the footwall side of the reverse fault, because there was insufficient capacity to accelerate the hanging wall upwards with available laboratory equipment. This change from expected field behavior would not change the test results for pseudostatically applied fault motions; however, it does have the potential to affect the results of dynamically applied fault motion, as acknowledged by the researchers [18].

Roth et al. [18] found that when the base movement was applied slowly it took less base movement to develop fully the shear banding through the soil than when compared to the case when the base movement was applied rapidly. In the case shown in Fig. 1, the shear band extends approximately to mid-height of the soil profile for the rapid base displacement case; whereas the shear band extended to the ground surface for the slow

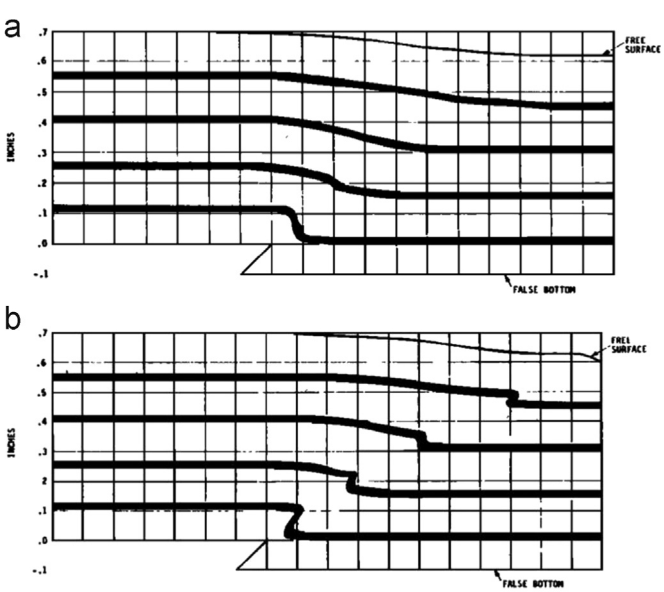

Fig. 1. Centrifuge test results for dense sand from Roth et al. [18] and Scott [19]: (a) fast fault movement (peak ground acceleration of approximately 0.5 g); and (b) slow fault movement (pseudostatic). For these tests the footwall was lowered rather than the hanging wall moved upwards. Slow fault movement resulted in more extensive shear band propagation and slightly shallower fault propagation dip compared to faster fault slip.

(pseudostatic) loading case. However, the deformed ground surfaces observed in the centrifuge tests for rapid and slow base displacement cases were qualitatively similar in most cases. Changes in the sand density produced larger differences in the observed ground surface deformation than changes in the base displacement rate. Soil properties play a more important role for modeling fault rupture propagation through previously unruptured soil.

Johansson and Konagai [20] also performed physical testing of rapidly applied base fault movement without transient shaking; however, these tests were conducted to assess the effect of an undrained loading on saturated sands rather than evaluating the effects of fault slip velocity. Interpretation of these results for dynamic effects is complicated by the need to separate the inertial effects from the undrained soil response. Neither the Roth et al. [18] or Johansson and Konagai [20] studies addresses the interaction of dynamically applied fault rupture with overlying structures, which will be addressed in this paper.

3. Numerical procedures and validation

The two-dimensional (2D), plane strain, explicit finite difference program FLAC [21] is employed with a modified version of the UBCSAND constitutive model [22] to assess the dynamic effects of surface fault rupture interaction with structures for the case of dip-slip faulting through sand. The same numerical procedures described in Oettle and Bray [23,24] were used herein with modifications for dynamic analysis, as noted below. The baseline soil model parameter values used for these analyses are provided in Table 1. These analyses were conducted for a 60° dip fault, 15 m-thick soil deposit, 0.3 m of vertical fault movement, $N_{1,60}=22$, and $K_0=0.45$, unless otherwise noted. The soil is treated as an engineered fill, with a drained response, that has not been previously ruptured by past earthquakes [23], except for a single scenario in which the effects of prior ruptures were evaluated.

Numerical damping is required in the explicit finite difference method to dissipate dynamic energy and prevent the model from continuously oscillating after application of the fault rupture. Damping was largely accounted for in the soil constitutive model through hysteretic damping in the UBCSAND [22] formulation. However, an additional 0.5% of Rayleigh damping was added to damp high-frequency motions. The minimum Rayleigh damping value was applied at the small-strain site period of the soil profile [21]. Damping within the structure was modeled using local damping [21] of 2% instead of Rayleigh damping to prevent a large decrease in the required time step.

The numerical model was configured initially to analyze the same fault and soil conditions reported in Roth et al. [18] to compare results of the numerical simulations against relevant experimental test results. However, these comparisons are qualitative, because the raw data of the Roth et al. [18] tests are not available, and the relative density and other relevant soil properties of the centrifuge tests were not reported in Roth et al. [18]. Furthermore, the direction in which base fault displacement was applied in these laboratory tests was the opposite of that expected in the field. The results of the numerical simulations and the centrifuge tests were qualitatively similar, except the previously noted difference in the amount of base displacement required to fully develop the shear band through the soil deposit in the centrifuge tests was not observed in the numerical simulations. The overarching finding from these numerical simulations and the geotechnical centrifuge tests described in Roth et al. [18] is that there are only relatively minor differences in the patterns of the deformed ground surface between the dynamic and pseudostatic cases for these test scenarios.