Reply to comment by N. Koizumi et al. on "Coseismic hydrological changes associated with dislocation of the September 21, 1999 Chichi earthquake, Taiwan"

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Received 31 March 2004; accepted 22 May 2004; published 2 July 2004.

INDEX TERMS: 1899 Hydrology: General or miscellaneous; 1829 Hydrology: Groundwater hydrology; 7299 Seismology: General or miscellaneous. **Citation:** Lee, M., T.-K. Liu, K.-F. Ma, and Y.-M. Chang (2004), Reply to comment by N. Koizumi et al. on ''Coseismic hydrological changes associated with dislocation of the September 21, 1999 Chichi earthquake, Taiwan,'' *Geophys. Res. Lett.*, *31*, L13604, doi:10.1029/2004GL020128.

[1] Thanks to *Koizumi et al.* [2004] for their comment on our paper. We have recalculated the coseismic static strains. It shows that, except in the proximity of the Chelungpu fault, the area to the west of this fault has positive volumetric strain (i.e., extension) as they have pointed out. The inconsistency between the patterns of the static volumetric strain and the hydrological phenomena during the Chichi earthquake is thus similar to the case of the 1995 Kobe earthquake [*Koizumi et al.*, 1996]. *Manga et al.* [2003] also reported that the streamflows of Sespe Creek, CA. always increased in response to earthquakes regardless of the polarity of the static volumetric strain. They suggested that the streamflows appeared to respond to the dynamic strain. The mechanism they adopted was the cyclic loading by seismic waves. This liquefaction mechanism is also suggested by *Wang et al.* [2001] and the comment of *Koizumi et al.* [2004]. Since the extension of rocks does not cause groundwater level rise, it is obvious that the extensional static volumetric strains were not the driving force inducing the hydrological phenomena occurred on the Choshui alluvial fan-delta. Besides, it seems that there is no mechanism for the relatively soft alluvium to carry tectonic rock stress. Accordingly, it leads to the idea, which we now suggest, of the liquefaction mechanism being the cause of the groundwater level rises on the Choshui alluvial fan-delta.

[2] *Rojstaczer et al.* [1995] studied the hydrological changes following the 17 October 1989 Loma Prieta earthquake in California. They found that the dropping water table was accompanied by the augmented streamflows. Similar observation was found by *Sato et al.* [2000]. The two major characteristics they described were: (1) drops of water tables occurred mainly in highland and inland; (2) increases of spring flows occurred mainly in lowland. Both studies suggested a permeability enhancement caused by seismically induced fractures and micro-fractures to account for the observed hydrological phenomena. In our study, all the wells located on the highland region of well-consolidated rock with earthquake intensity more than six showed water level falls. In addition to the water table falls on the highland, the significant streamflow increases occurred at many gauging stations from central west to northern west Taiwan soon after the Chichi earthquake. We suggest that these hydrological phenomena were attributed to two possible causes related to earthquake shaking: (1) permeability enhancement of rock in the mountain area [*Rojstaczer et al.*, 1995]; (2) releasing of water from partially saturated unconfined aquifers, terrace, and valley-bottom deposits by dynamic straining [*Manga et al.*, 2003; *Montgomery et al.*, 2003].

[3] Most data that pertain to the cause, process, and effect of liquefaction (and cyclic mobility) come from engineering studies. There has not been any observation of liquefaction at depth greater than 30 m historically. Therefore, the behavior of porewater pressure excitation in alluvial deposit subjected to dynamic shear stress under high confining stress has not been explored extensively. *Sharp and Steedman* [2002] (see http://www.pwri.go.jp/eng/ujnr/joint/34/paper/43sharp.pdf) reported a centrifuge test to investigate high confining stress effects on liquefaction potential of fine and clean Nevada sand. Their results indicated that the excess porewater pressure would develop at high confining stress of 3 to 12 atm. For example, the excess porewater pressure after shaking would reach 55% of the effective overburden stress under equivalent field depth of 63 m. The highest groundwater level rise in the Choshui alluvial fan-delta is about 7 m in the confined aquifer F-2 [*Lee et al.*, 2002, Figure 2b]. If the groundwater level rise was induced by shaking, it means the excess porewater pressure reached 7% of the effective vertical stress at the depth of about 100 m. It is reasonable to believe that the coseismic groundwater level rise is related to the tendency of cyclic mobility. Since the dynamic strain by shaking is contraction in the Choshui fan-delta, the explanation of the "bull-eyes" pattern in Figure 3 of *Lee et al.* [2002] need not be modified. The sequence of the coseismic excess porewater pressures of four aquifers are, from the lowest to the highest, F-1 (unconfined aquifer), F-4, F-3, and F-2 [*Lee et al.*, 2002, Figure 2]. It seems that the excess porewater pressure of the confined aquifers decreased with the depth of the aquifers. One possible explanation is that the deeper the aquifer is, the more effective vertical stress, aging and degree of cementation it has been experienced. Since the strain sensitivity is frequency dependent, we expect that the value calculated from dynamic strain will probably be

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0094-8276/04/2004GL020128$05.00

different from that calculated from the long-periods earth tides response.

[4] However, two facts should be considered before jumping into the conclusion that coseismic groundwater level rise in the Choshui alluvial fan-delta was caused by the tendency of cyclic mobility. First, the depositional ages of the confined aquifers in the Choshui alluvial fan-delta range from ca. 27,000 to greater than 50,000 years B.P. [*Liu*, 1995]. Aging and cementation might influence the dynamic response of the deposits at the depth of 100~300 m. Secondly, the Chelungpu Fault has been active since Middle Pleistocene (ca. 0.7–0.5 Ma) and has triggered large earthquakes with average recurrence interval of less than 700 years [*Chen et al.*, 2004]. Hence, the confined aquifers might have been shaken by large earthquakes induced by the Chelungpu Fault for more than 40 times since their deposition, not to mention the frequent large earthquakes from other part of Taiwan. Therefore, the alluvial deposits should have been presheared many times and the dynamic response of the deposits might have been influenced. Further study is needed to verify, quantitatively, the development of coseismic excess porewater pressure in the Choshui alluvial fan-delta at effective stress ranging from 1 to 3 MPa.

[5] **Acknowledgments.** We thank Prof. Mike Gladwin and Dr. Shiann-Jong Lee for many discussions on dislocation model. We also appreciate the comment on liquefaction by Prof. Jia-Jun Dong.

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