The sources of permanent ground deformation of most importance during the 921 earthquake are landslides and surface faulting. Although there was evidence of liquefaction in fills at the Taichung port facilities and in alluvial soils throughout the epicentral region, the influence of soil liquefaction on the built and natural environments was not as pronounced as the effects of landslides and surface faulting.

**LANDSLIDES**

There were literally scores of thousands of landslides in the mountainous terrain within and adjacent to the epicentral area. Most slides were relatively shallow slips in residual soils, typically involving depths of 2 to 5 m. A large proportion of the landslides were considerably deeper and broader. The largest landslides were located at Tsao-Ling Mountain near the village of Tsao-Ling and Jio-Feng Err Mountain near the village of Nangkang. These landslides mobilized millions of cubic meters of rock and soil that slid across adjacent rivers, creating large landslide dams. River blockage, especially at Tsao-Ling, was accompanied by the formation of lakes that are flooding the upstream river valleys. As water rises, there is the potential for overtopping and downstream flooding.

Figure 1a and b shows views of the landslide at its eastern and western margins, respectively. The landslide is at the location of previous landslides that occurred in 1941, 1942, and 1979. The landslide was generated primarily by failure of the Chin-Shui Shale Formation that underlies the Chao-Lan Sandstone (see Figure 1b). The shale is a friable, silty mudstone with weak cementation that deteriorates readily upon wetting and drying.

**Recommendations for Short-Term Recovery**

Plans are needed to deal with the landslide dams along the Ching-Shui and Wushi Rivers. Landslide dams in the 1940s and 1979 at the Tsao-Ling site and subsequent flooding when the dams were overtopped provide valuable data and experience with which to approach the problem. In developing a plan, it will be advantageous to calculate the volume of each landslide dam. Consideration should be given to the inflow rate, maximum volume of water stored, potential for accelerated filling due to tropical storms and typhoons, upstream and downstream flooding, and options to mitigate the problem. Mitigation options include, but are not limited to partial excavation to reduce maximum impoundment levels, construction of overflow structures or diversion tunnels/conduits, blasting to release the water, and monitoring and eventual downstream evacuation.

An assessment of the remaining landslide and debris flow potential would be useful to identify communities and lifelines at risk from continued slope failure both within and downstream of the deforested mountain areas. Debris flow hazards are especially severe because the earthquake has loosened and failed a considerable amount of soil and rock in addition to exposing deforested mountains and hillsides to the elements. Consideration should be given to how drainage features and flow paths have been altered by the earthquake.

Plans need to be formulated for the reconstruction of Route 8 that take account of the increased vulnerability to landslides associated with fractures and loosening of the weathered rock as well as its increased exposure to precipitation caused by the earthquake. The plans should balance risk mitigation related to control of future landslide activity with the need for rapid reinstatement of the road.
Research Needs
There is the need for a comprehensive decision support system to identify and rank landslide hazards and evaluate their impact on communities and lifelines. Whereas such a system should be calibrated for earthquakes, it should extend also to the influence of factors such as storms and floods. The opportunity exists for taking advantage of advanced remote sensing technologies and geographic information systems (GIS) to develop a graphical, multi-hazard approach to the problem (see Applications of Remote Sensing, page 14).

Surface Faulting
Some of the most notable ground failures associated with the 921 earthquake were related to the vertical and horizontal offsets generated by rupture of the Chelungpu fault. Vertical fault offsets in Feng-Yuan were as high as 4 to 5 m, and were responsible for extensive building damage and collapsed structures. Surface faulting was also responsible for the failure of the Tung-Feng Bridge and Shih-kang Dam, both of which spanned the Tachia Hsi River to the east of Feng-Yuan.

Fault rupture with a vertical offset exceeding 9 m was responsible for failure of the Shih-kang Dam and subsequent release of millions of cubic meters of water. This loss represents 40% of the raw water supply for Taichung County. Figure 2a is a photograph of the northern abutment area taken downstream of the dam, and Figure 2b is a photograph of the northern abutment from the vertically displaced southern part of the dam.

The effects of surface faulting in the 921 earthquake are broadly similar to the surface faulting effects of the August 17, 1999 Kocaeli earthquake in Turkey. Rupture of the Northern Anatolian fault during the Kocaeli earthquake caused a highway bridge to collapse and caused extensive damage to the main Turkish naval base in Golcuk. Recent major earthquakes, such as the 1994 Northridge and 1995 Kobe earthquakes, were not accompanied by surface faulting in heavily populated areas. The presence of severe surface faulting in both the 921 and Kocaeli earthquakes demonstrates how destructive and disruptive surface faulting can be, and encourages a more careful consideration of such effects along active faults in Taiwan and the U.S.

Recommendations for Short-Term Recovery
The rupture of the Chelungpu fault differs at its northern end from the surface trace that was mapped and reported on the most recent active fault maps of Taiwan. The fault appears to turn sharply to the east just north of Feng-Yuan where it intersects the northern side of the Shih-kang Dam. In the short-term, it is important to clarify the mechanism of fault rupture in this area and to define better the fault trace and its surface characteristics. Delineating the main fault rupture and establishing the occurrence of subsidiary ruptures, including coseismic movements on the nearby Tamoupu-Hsuangtung fault, are important for an improved understanding of both the near field transient and permanent ground deformations generated by the earthquake. Locating the active trace and strands of the Chelungpu fault is also important for evaluating various options with respect to restoration of the Shih-kang Reservoir.

Plans need to be made for recovery of the water supply in Taichung County. Of key importance for this restoration is a vulnerability assessment of the Shih-kang Reservoir site with respect to renewed movement of the Chelungpu fault. The reservoir is a critical facility, and relocation will be difficult, if not impractical. It may be important therefore to utilize as much of the current site as possible. Future use of the Shih-kang Reservoir requires careful consideration not
only of the Chelungpu fault and subsidiary ruptures, but of the current elevation differential at site, relocation of all or part of the dam, and the re-use, if any, of existing undamaged portions of the dam.

Restoration of the Taichung water supply is a complex problem that requires a systems approach. For example, it may be advantageous to convey water from neighboring water sheds via new transmission pipelines, rather than rehabilitate the entire Shih-kang site. A comprehensive plan should include a full assessment of current earthquake damage to the reservoirs, treatment plants, and distribution network.

Research Needs
The destructive consequences of surface rupturing along the Chelungpu fault, which was identified as a relatively low risk Category II fault, raises important questions about hazard identification and siting of critical structures in the vicinity of active faults. Land use and development at California faults are controlled by state legislation, known as the Alquist-Priolo Act, that places substantial restrictions on new construction in active fault zones. Land use planning in Taiwan must take account of its high population density and limited options for land use. It will be advantageous to consider a more systematic approach to fault mapping, assessment of rupture hazard and risk, and potential establishment of zoning and siting guidelines, especially for critical structures.

Locations of underground pipelines crossing the Chelungpu fault provide excellent opportunities to evaluate the performance of such facilities subjected to varying levels of differential fault offset. Of special interest are welded steel pipelines for water trunk and transmission operations, high pressure natural gas and liquid fuel, and oil insulated electric cables. The pipeline age, diameter, wall thickness, type of steel, burial depth crossing angle, and locations of adjacent bends and tees should be documented in addition to soil type, pipe condition, and repairs.

Reconnaissance observations have shown that many structures, immediately adjacent to, but not located in the path of fault rupture were apparently not seriously damaged. This observation applies even to non-ductile concrete frames and unreinforced masonry structures. Similar observations have been made for the Kocaeli earthquake. A systematic assessment of structures immediately adjacent to the Chelungpu fault, but not subject to permanent ground deformation, would help to clarify structural performance and apparent dynamic response very near the fault.