Characterizing Fault Rupture Hazards for Design of Buried Pipelines

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Location of buried pipelines may not be able to avoid fault traces that have the potential to rupture the ground surface. For detailed hazard analysis, geologic evaluation must be done to determine the age and recurrence intervals of surface faulting events. These data, along with the proximity to population as an index of public risk, are used to identify those faults that require pipeline treatment for design. Detailed geologic evaluation also allows characterization of fault movement for pipeline stress analyses. The type of fault, orientation of the fault with respect to the pipeline, direction of movement, and amount of movement must be quantified for stress analyses. The design procedure is iterative and can be done with an analytical or a finite-element method. Variable parameters in the design are unanchored length, pipeline-fault intersection angle, ditch geometry, backfill material properties, pipe material, and pipe coating.

Linear facilities, such as canals and pipelines, cannot be located to avoid all linear geologic features, such as rivers and faults. Active processes associated with unavoidable linear geologic features must be characterized to provide a basis to (*a*) reduce the risk of damage to the facility, which could result in a threat to public safety; (*b*) reduce the owner's exposure to loss of facility function; and (*c*) comply with mitigation measures required by federal, state, or local agencies, such as the Federal Energy Regulatory Commission (FERC).

Design of buried pipelines exposed to surface fault rupture hazards is discussed. Faults in the vicinity of pipeline alignments must be evaluated to identify potentially hazardous movements. Fault movement parameters must be defined for those considered hazardous. The parameters provide the geologic basis for an iterative design process that allows adjustment of several variables so that stresses, strains, and deformations remain within the allowable range. The procedure described in this paper can also be used for design of pipelines crossing sites that have similar potential ground movements, such as landslides and liquefaction zones.

HAZARDOUS FAULTS

A fault is a plane across which displacement of opposite sides has occurred parallel to the plane. A fault zone is a zone of such planes that may merge at depth into a single plane. Displacements across faults can be purely parallel to the strike of the plane (strike-slip faults), purely parallel to the dip of the plane (dip-slip faults), or a combination of the two directions (oblique-slip faults). Idealized slip alternatives are shown in Figure 1.

Hazardous faults are those faults that are "active" (*2*) or "capable" (*3*). An active fault is one along which movement will occur in the future. Sites that have had fault movement in the recent past may be more likely to have future movements than sites that have not had recent fault movements. The length of time appropriate to represent the recent past has been the subject of much discussion within the geologic community. State and local ordinances regulating development in areas with known fault traces commonly are based on the most recent 10,000 years of earth history (Holocene time). FERC defines capable faults as those that have moved at least once during the past 35,000 years (late Pleistocene time) or multiple times during the past 500,000 years (late Quaternary time). Thus, the degree of hazard may be expressed by the age of the most recent movement and the recurrence interval between movements. For example, faults can be distinguished on some maps by age of most recent movement, as indicated in Figure 2.

In some areas of less frequent earthquake activity, faults may appear to have been inactive for long periods but be oriented in such a way that they might be expected to move again under the current stress field. The orientations of faults and folds associated with simple shear in a strike-slip fault zone are shown in Figure 3. Thus, if a fault trace were identified in an area of interest but the geologic record needed to determine the age of most recent movement were missing, the potential for future activity could be based on its relationship to the stress field associated with the nearest known active fault.

Not all faults that were active during Quaternary time represent the same hazard in terms of frequency or amount of surface displacement (*1*,*6*). Therefore, not all Quaternary faults represent the same risk of damage to pipelines. Furthermore, although many pipelines pass through urban areas, most pipeline alignments that cross active faults are remote from populated areas. An approach has been developed for three categories of pipeline treatment at active fault crossings: full design treatment, contingency-planning treatment, and no treatment (*7*). This approach uses geologic factors to screen the faults crossed by pipelines and is based in part on proximity to populated areas, as discussed below.

Fault Evaluation Procedure

The first task in a fault evaluation is to examine published geologic maps and reports and inventory fault traces and ages of displaced deposits. In many cases, published geologic maps were made to show bedrock relationships, and Quaternary deposits and fault traces are generalized.

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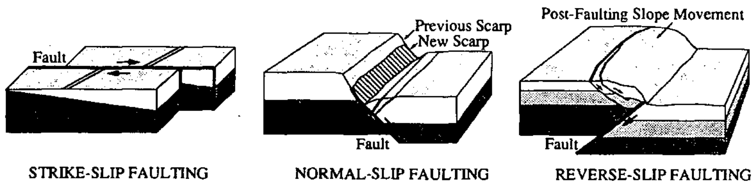

FIGURE 1 Idealized types of faults [modified from Slemmons (*1*)].

The second task is to examine aerial photographs for lineaments, particularly in deposits or across surfaces of Quaternary age. The most detailed photographs may not provide adequate information because they may cover only a limited area along a project. For example, photographs taken specifically for a pipeline project are usually oriented along a single flight line parallel to the project and often do not extend far enough from the alignment to be useful for fault evaluation. A pipeline alignment may cross a fault in an area where the fault is concealed by very young deposits, and photographs taken along the strike of the fault or with multiple flight lines may be needed for fault evaluation. Consequently, aerial photograph coverage may be supplemented with photographs from available federal agency collections (Soil Conservation Service and Forest Service, U.S. Department of Agriculture, and Bureau of Land Management and Geological Survey, U.S. Department of the Interior). Photographs taken at several times of the year may be useful for vegetation contrasts that may be present along fault traces. One of the most useful scales for fault evaluation is 1:12,000 because a reasonable area is visible in a single view at reasonable detail. A standard 9-in. (22.9-cm) contact print covers an area of 9,000 ft (2.74 km by 2.74 km) and can be viewed at a scale of about 1:2,400 with a conventional stereoscope with 5-power magnification.

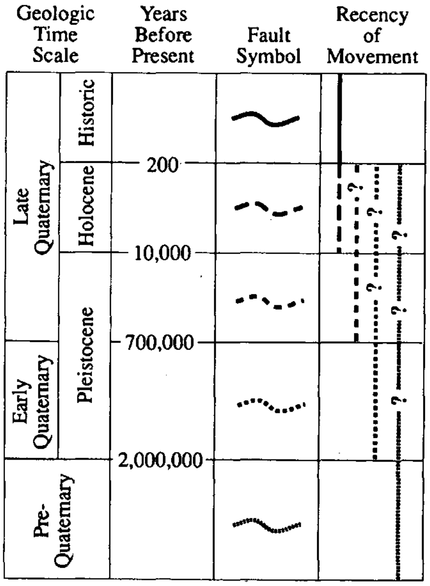

FIGURE 2 Distinction of faults by age of most recent movement [modified from Jennings (*4*)].

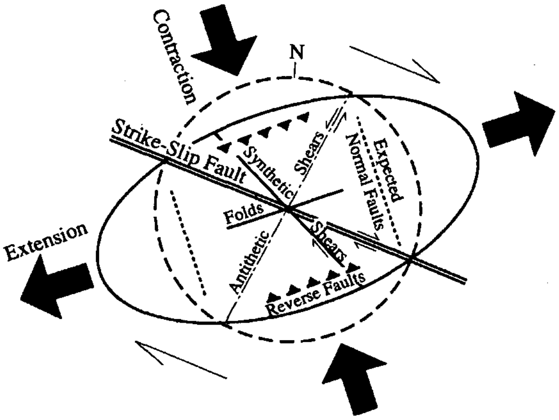

FIGURE 3 Orientations of faults and folds associated with simple shear in a strike-slip fault zone [modified from Keller (*5*)].

The third task is aerial reconnaissance of the project area and faults and lineaments previously identified. Aerial reconnaissance during low-sun-angle illumination enhances shadows cast by scarps facing away from the sun and bright lineaments caused by reflectance from scarps facing toward the sun. The shadow and highlight enhancement can be particularly valuable for identifying subtle or low scarps in young sediments along Quaternary faults. It may be useful for selected segments of a project and possible fault-related features to be photographed at a scale of about 1:12,000 under low-sun-angle lighting.

Following examination of the low-sun-angle photographs, the fourth task is detailed field mapping of locations most promising to yield data regarding (*a*) whether lineaments are actually faults, (*b*) the age of most recent activity, and (*c*) likely recurrence intervals between surface faulting events.

The fifth task is preparation of a summary fault characterization listing

1. Fault type (strike-slip, normal-slip, reverse-slip),
2. Orientation with respect to the pipeline (angles of intersection are referenced to the pipeline as viewed in a downstream direction; positive angles are to the right and negative angles are to the left of the pipeline axis),
3. Direction of movement (such as right-lateral, down-to-the-southwest, up-from-the-north),
4. Probable age of most recent movement (estimated in years, such as >10,000 years), and
5. Amount of movement per fault rupture event (estimated in feet or meters).

Fault type, orientation with respect to the pipeline, and direction of movement are straightforward parameters that require no further explanation. The probable age of most recent movement and recurrence intervals can be estimated from geologic relationships involving the youngest faulted material and the oldest unfaulted material. The degradation of fault scarps in alluvial deposits can be used to estimate the age of the most recent movement, and the shape of the scarp can be used to estimate the number of surface faulting events responsible for creating the scarp (*8*).

The amount of fault movement per event can often be determined from the height of scarps in young sediments or the distance stream channels have been offset. Scarps in very young sediments may record only one surface faulting event; therefore, the height of the scarp may be a reasonable estimate of the amount of fault movement expected during the next event. The scarp along the entire length of a fault trace should be examined to determine the maximum single-event scarp height, which is the height that should be used for design (*9*). Subsurface investigations often provide the best information regarding the vertical component of displacement in past fault rupture events. Geomorphic evidence of lateral slip along faults, such as offset stream channels, often provides the best estimate of the amount of movement; estimating the age of such movement can be particularly challenging. Maximum displacements may be estimated on the basis of field data and relationships between fault rupture length and earthquake magnitude displacement (*10,11*).

Proximity to Populated Areas

For some projects, public risk exposure may be an important issue. The population classifications of the U.S. Department of Transportation (DOT) (*12*) for natural gas pipelines are based on the distance from pipelines to number of buildings within certain areas. The DOT classification is summarized in Table 1.

Fault Crossing Philosophy

A philosophy for design of pipelines crossing active fault traces is illustrated in Figure 4. This philosophy was developed for the Kern River pipeline project, which extends from southwestern Wyoming to southern California and crosses the seismically active Basin and Range Province with its numerous Quaternary faults (*13*). Three design treatment options were considered: no treatment, operational treatment, and full treatment. No treatment was considered necessary for the design of the pipeline where it crossed faults that seemed to pose little risk to the project and were relatively remote from populated areas. Operational treatment consisted of a contingency plan for rapid repair of the pipeline where it crossed faults that seemed to pose some risk to the project but were relatively remote from populated areas. Full treatment consisted of controlling six variables, discussed later in the section headed Summary of Design Procedure, where the pipeline crossed hazardous faults in relatively close proximity to populated areas.

TABLE 1 U.S. Department of Transportation Population Classifications for Areas Crossed by Natural Gas Pipelines [adapted from DOT pipeline safety regulations (*12*)]

DOT Population Classification	Number of buildings within 200 m on either side of the centerline of any 1.61-km length of pipeline
1	0 to 10
2	11 to 45
3	46 or more, or within 100 m of a place occupied by 20 or more persons on at least 5 days per week, 10 weeks per year
4	Class 1, 2, or 3 where buildings of 4 or more stories are prevalent

FAULT RUPTURE DESIGN PARAMETERS

If fault rupture must be included in pipeline design, it must be described in a way that can be used to compute stresses, strains, and deformations in the pipe material. Fault rupture design parameters are (*a*) fault orientation, (*b*) direction of movement, and (*c*) amount of movement. The orientations of fault traces can usually be determined from observation of scarps and other surface features created by past faulting events. The dip of the fault plane may be somewhat more difficult to determine from surface observations. The direction of movement should be clear from the surface expression and the seismotectonic setting. For example, northwest-trending faults in southern California are right-lateral strike-slip faults, and north-trending faults in Nevada and Utah are normal faults. Subsurface investigations may be needed to locate the fault at the pipeline crossing; however, the amount of movement visible in a trench exposure may be less than the maximum displacement, which is the value that should be used in calculating stress and strain.

Logs of trenches excavated across a normal fault and a strike-slip fault are shown in Figures 5 and 6, respectively. The Granger fault, part of the West Valley fault zone near Salt Lake City, is a north-trending normal fault with no lateral component to the movement; therefore the vertical displacements of layers visible in a trench (Figure 5) represent the true character of the fault movement. Important aspects of the fault shown in Figure 5 are that it is relatively narrow (less than 1 m wide) and movement has occurred repeatedly along the same plane. The average displacement per event at the Granger fault is estimated to be about 1.5 m (*14*), yet the displacement of the Bonneville alloformation in Figure 5 is greater than 4.3 m, suggesting that at least three surface faulting events occurred in post-Bonneville time (the past 12,000 years). The Coyote Creek fault, near Anza Borrego State Park in southern California, is a northwest-trending strike-slip fault with little vertical component to the displacement; therefore the vertical displacements of layers visible in a trench (Figure 6) do not represent the true character of fault movement. In fact, the displacements of layers are apparent vertical separation due to lateral displacement of gently inclined beds. Important aspects of the fault shown in Figure 6 are that it is relatively narrow (less than 1 m wide) and movement has occurred repeatedly along the same plane. The vertical dis-

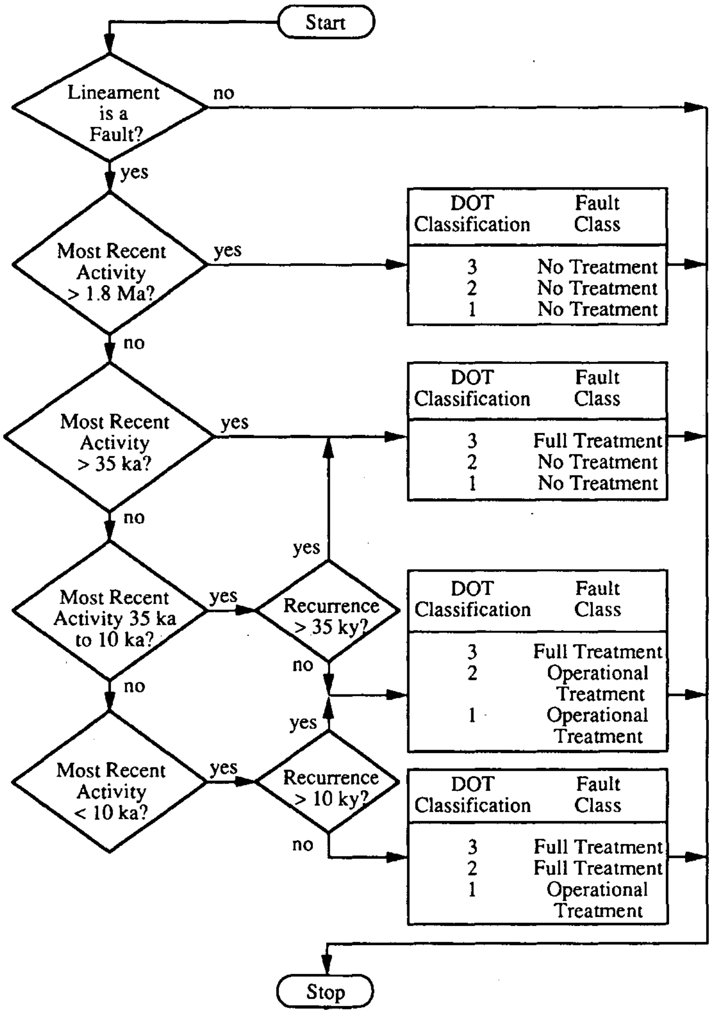

FIGURE 4 Flow diagram for treatment of the Kern River pipeline at active fault crossings [modified from Keaton et al. 1991 (*7*)].

placement values shown in Figure 6 indicate a slip rate of about 0.6 m per 1,000 years; however, the slip rate based on lateral offset of geomorphic features is about 3 m per 1,000 years (*15*).

The most reliable method of estimating the amount of fault rupture movement for use in stress analyses is direct observation of displaced features of known age. An alternative method of estimating maximum displacements associated with future fault rupture is statistical analyses of displacements cause by historic earthquakes, such as those by Bonilla et al. (*11*) and by Slemmons et al. (*10*). However, improper use of regression equations can result from careless application of statistical analyses (*16*). Since fault displacement is needed for stress analyses, displacement is the dependent variable. The appropriate independent variable would be fault length if it is estimated from published geologic maps or reconnais-

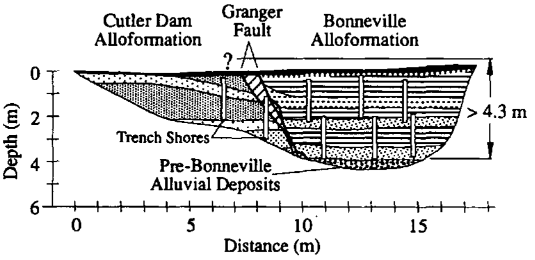

FIGURE 5 Log of trench across the West Valley fault [modified from Keaton et al. 1987 (*14*)].

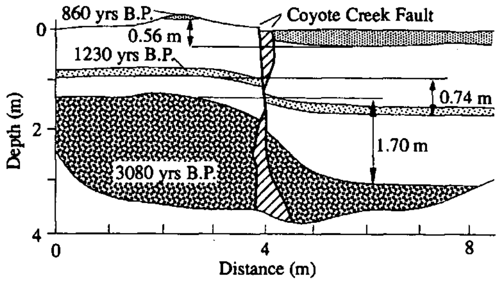

FIGURE 6 Log of trench across the Coyote Creek fault. [modified from Clark et al. (*15*)].

sance mapping. However, improper use of the regression equations results if earthquake magnitude is predicted from fault length and displacement is then predicted from earthquake magnitude.

As an example of fault displacement parameters, the values used in the design of the Kern River pipeline at its crossing of the Calico fault, the Antelope fault, and the Wasatch fault are presented in Figures 7, 8, and 9, respectively. The Calico fault is a northwest-trending, right-lateral strike-slip fault in the Mojave Desert of southern California. The Kern River pipeline crosses the Calico fault on gently sloping ground at an angle of +68 degrees. The Antelope fault is a north-northwest-trending, down-to-the-west normal fault in southwestern Utah. The Kern River pipeline crosses the fault on gently sloping ground at an angle of −50 degrees. The Wasatch fault is a north-trending, down-to-the-west normal fault in north-central Utah. The Kern River pipeline crosses the fault on steeply sloping ground at an angle of −45 degrees.

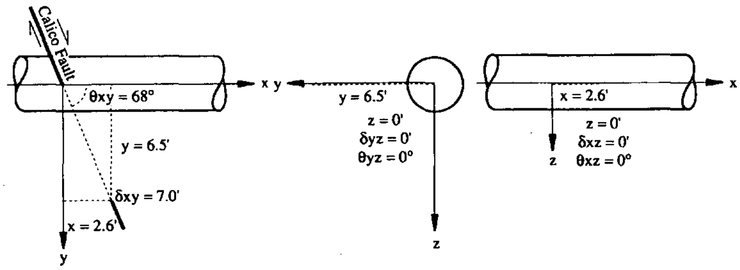

FIGURE 7 Design fault displacement parameters for the Calico fault crossing of the Kern River pipeline [modified from reports by Sergent, Hauskins & Beckwith (*17*)]. The reference coordinate system is oriented so that the positive *x*-direction is along the pipeline axis in the direction of increasing pipeline station numbers, the positive *z*-direction is perpendicular to the pipeline in a downward direction, and the positive *y*-direction extends to the right. ***θxy***, ***θyz***, and ***θxz*** are the angles between the fault plane and reference coordinate system axes in the respective planes. **δ*xy***, **δ*yz***, and **δ*xz*** are the displacement vectors in the respective planes. ***x***, ***y***, and ***z*** are the orthogonal components of displacement.

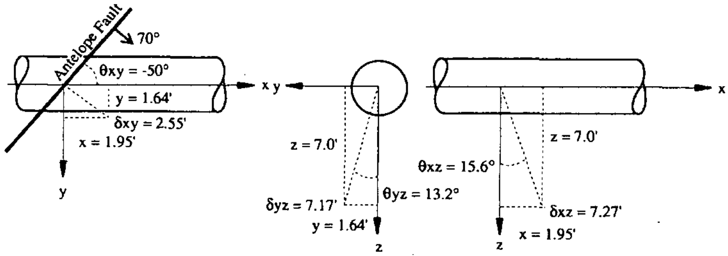

FIGURE 8 Design fault displacement parameters for the Antelope fault crossing of the Kern River pipeline [modified from reports by Sergent, Hauskins & Beckwith (*17*)]. See Figure 7 for explanation of coordinate system and symbols.

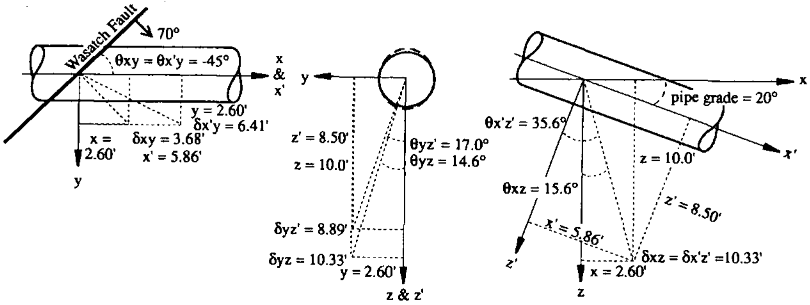

FIGURE 9 Design fault displacement parameters for the Wasatch fault crossing of the Kern River pipeline [modified from reports by Sergent, Hauskins & Beckwith (*17*)]. See Figure 7 for explanation of coordinate system and symbols.

Sloping ground and angle of crossing result in apparent lateral displacement due to normal-slip fault movement and apparent vertical displacement due to strike-slip fault movement.

SUMMARY OF DESIGN PROCEDURE

The following brief summary of the design procedure demonstrates the application of fault rupture parameters; the Kern River pipeline project is used as an example. An analytical method (*18*) and two finite-element methods [PIPLIN-PC (*19*) and B-SPLINE (*20*)] are in common usage. The pipeline design parameters are unanchored length, intersection angle, ditch geometry, backfill characteristics, pipe material, and pipe coating.

The unanchored pipeline length allows strain to be distributed. An unanchored length of 200 pipe diameters was used for the Kern River pipeline [approximately 180 m (600 ft) for the 91.4-cm (36-in.) diameter pipeline] on the basis of work by Newmark and Hall (*21*), Kennedy et al. (*18*), and Roe (*22*). Heavy-wall pipe [1.57 cm (0.618 in.) thick] made of API X-70 steel has favorable stress-strain characteristics and can accommodate substantial deformation while remaining anelastic. A soil-pipe friction angle of 14.3 degrees was estimated for the epoxy coating of the pipe (Shore D hardness of 84) on the basis of studies by O'Rourke et al. (*23*). Analytical procedures by Kennedy et al. (*18*) and the PIPLIN-PC finite element computer program (*19*) were used to perform soil-pipe interaction analyses to evaluate pipe stresses and strains for various backfill configurations to optimize the treatment. Medium-dense sand [ϕ = 35 degrees, γ = 18.85 kN/m^3 (120 lb/ft^3)] was specified for backfill around and beneath the pipe. Force-displacement relationships (*p-y* curves) (Figure 10) for the backfill were determined by procedures of Audibert and Nyman (*24*), Nyman (*25*), Trautmann et al. (*26*), and Trautmann and O'Rourke (*27*) for use in the analysis. The configuration of the ditch provides overexcavation of the bottom on the footwalls of normal faults and widening the sidewalls across the strike-slip faults, as shown in Figure 11. For the type and amount of fault movement assumed in the design, the analysis indicated that the ditch configuration would limit tensile strains in the pipe to less than 2 percent. The pipe was oriented at strike-slip and normal-slip fault crossings so that it will be in tension for the design fault displacements.

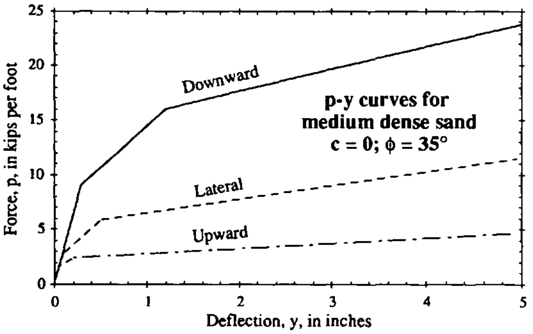

FIGURE 10 Load-deflection characteristics for medium-dense sand backfill [modified from reports by Sergent, Hauskins & Beckwith (*17*)].

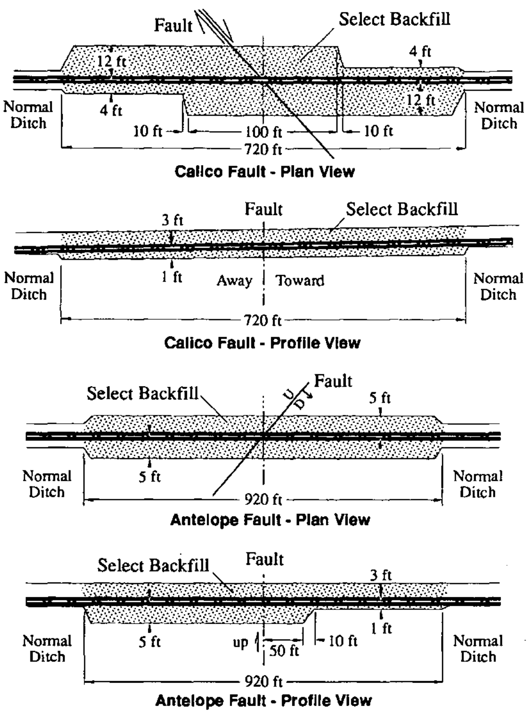

FIGURE 11 Construction ditch geometries for crossing active faults [modified from reports by Sergent, Hauskins & Beckwith (*17*)].

CONCLUSIONS

Hazardous faults can be identified and characterized with conventional detailed geologic studies. A risk-based philosophy for treatment of pipelines crossing active faults has been developed that appears to be conservative, particularly in remote (DOT classification 1) areas. Stress analyses using API X-70 steel, appropriate backfill *p-y* curve data, pipeline-fault geometry, and maximum fault offset amount from detailed geoseismic analyses allow one to determine the ditch dimensions needed to limit stresses and strains in the pipe. An analytical procedure (*18*) and a finite-element method (*19*) are commonly used in this context.

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