Design Features of an 18.5-Foot Diameter Culvert Installation in Montana and Data on Subsequent Failure

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The natural topographic features of a winding mountainous canyon combined with additional restrictions imposed by an existing railroad and stream were the basic factors which influenced the alignment and grade selection for a portion of I15 in west central Montana. A profile requiring a 100-ft high fill, flanked by highway centerline cut depths of 175 ft and 95 ft on either side, dictated the selection of an enclosed pipe conduit to convey the canyon stream across I15. An 18.5-ft diameter structural plate circular pipe was selected and designed by the ring compression theory. The pipe was installed without instrumentation as part of a construction contract for 2.3 mi of Interstate highway.

Six months after initial completion of pipe fabrication, and two months after completion of the embankment over the pipe to full height, major ruptures in the pipe were discovered. The distressed condition of the pipe was so extreme as to require removal and reconstruction of a large portion of it.

This paper will present data covering physical features of the project site in their relationship to the selection of a pipe, basic design data and features of the pipe, and information and pictures of the failed pipe. A paper dealing with the examination of failed bolts taken from the culvert and special testing of the type of high strength bolts used in the culvert has been prepared by the Armco Steel Corporation.

•I15 IS THE only continuous north-south Interstate route through the state of Montana. Two of Montana's principal cities, Great Falls and Helena, lie 90 miles apart on the center portion of this route.

A study of several alternate locations to traverse the moderately elevated mountains between Helena and Great Falls resulted in the selection of the same canyon occupied by primary highway US 91, a spur line of the Great Northern Railway and a large creek.

The task of preparing a reconnaissance study for location of the Interstate, along with subsequent final design and plans preparation, was assigned to Morrison-Maierle Inc., Consulting Engineers, of Helena. A major decision was to use an earth fill approximately 100 ft high with a buried culvert at a particular crossing of Little Prickly Pear Creek (Fig. 1). The existing ground on one side consisted of a near-vertical solid rock face. The opposite side was also largely solid rock covered with talus and a thin soil mantle but with a natural ground slope of 1¼:1 (Fig. 2). Construction blasting procedures resulted in embankment rock pieces of under 1 cu yd in size for the most part. The borings taken at the culvert location revealed bedrock at a depth of 20 ft below the streambed and overlaid with silty sandy gravel.

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Figure 1. Sketch of completed Interstate—note culvert.

CULVERT REQUIREMENTS

The 50-yr design flow was established at 3200 cfs. Numerous design trials were made with various pipe types and sizes, invert slopes and multiple pipes. This resulted in the final selection of a single structural plate pipe of 18½-ft diameter on an invert slope of 0.456 percent. Stream velocities with this slope would vary from 3 ft per sec at normal low flows of 25 to 50 cfs to 12.8 ft per sec at a flow of 3200 cfs. A camber of 0.4 ft was added at the quarter points. The use of this pipe size and slope resulted in the invert being placed 2 to 3 ft below the existing stream bed.

A reinforced concrete inlet headwall completely surrounding the pipe was used at right angles to the end of the pipe (Fig. 3). A 12-in. radius rounding of the inlet edges formed into the concrete was used to increase the capacity characteristic of the inlet. A reinforced concrete headwall was also used at the outlet, but it does not completely encircle the pipe. The top of it is 14 ft above the bottom of the pipe. It is tied into a concrete apron with a flat bottom and sloping sides which extend 15 ft beyond the end of the pipe. This structure provides protection to the abutments of a railroad bridge under which the pipe passes, and will prevent scour at the culvert outlet. Heavy riprap extends for another 63 ft beyond the apron where a concrete sill 32 ft long extending across the stream is located. The top of the concrete sill and the pipe outlet invert are at the same elevation, while the concrete and riprap aprons between the two are both 2 ft lower in elevation. This provides a pool and more resistance to scour at the outlet of the culvert.

Figure 2. Outlet end of culvert during construction.

Figure 3. Inlet end of culvert during construction.

A value of 105 lb per cu ft for the full vertical height of fill above the pipe was used for strength design. The actual weight of the embankment material, since it would be primarily rock, could be expected to be 130 lb per cu ft or more. However, considering the foundation material, the anticipated arching action in the rock embankment, and accepted practice in reduced unit weight for culvert design, the value to be used was established at 105 lb per cu ft.

A fill height over the pipe of 83 ft resulted in a unit load of 8.72 kips per sq ft. Considering the culvert as a compression ring, the load per foot of longitudinal seam was computed to be 76.6 kips, based on the reduced pipe diameter of 95 percent due to fabrication of the pipe to a 5 percent ellipsed shape. Standard 1 gage thick corrugated structural plate with the maximum number of standard bolts of 8 per lineal ft of seam provides an ultimate seam strength of 220,000 lb per lineal ft. This would provide a safety factor of 2.9. It was decided that this was too low for an installation of this magnitude and importance. Acceptable culvert practice has been based on the use of a safety factor of 4 for handbook type installations, where average backfilling practice is to be expected. On carefully controlled and well engineered installations a safety factor of 2 based on seam strength has been adequate in some cases. Test data furnished by the Armco Steel Corporation at the time of this design indicated that seam strength could be considerably increased with the use of corrugated ⅜-in. thick ingot iron plate. Eight standard high-tensile ¾-in. ASTM A 325 bolts with 120,000 psi ultimate tensile strength provided an ultimate tested seam strength of 226,000 lb per lineal ft in this material. The use of 8 ¾-in. ASTM A 354 high strength bolts with 150,000 psi ultimate tensile strength resulted in an ultimate seam strength of 270,000 lb per lineal ft. The use of the latter combination was decided on since it provided a safety factor of 3.5.

To provide more latitude for bidding competitors, the seam strength requirement specified was for a minimum of 250,000 lb per lineal ft of seam, which would still supply a safety factor of 3.25. Proof, using actual test data showing that this strength could be attained, was required of the contractor. Proof submitted by the installer

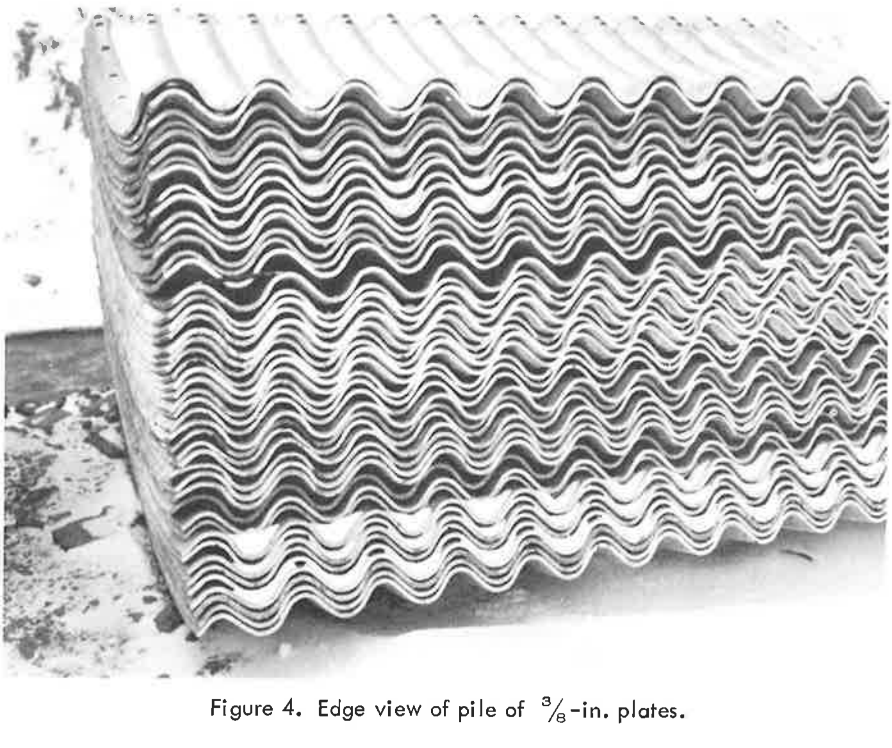

Figure 4. Edge view of pile of ⅜-in. plates.

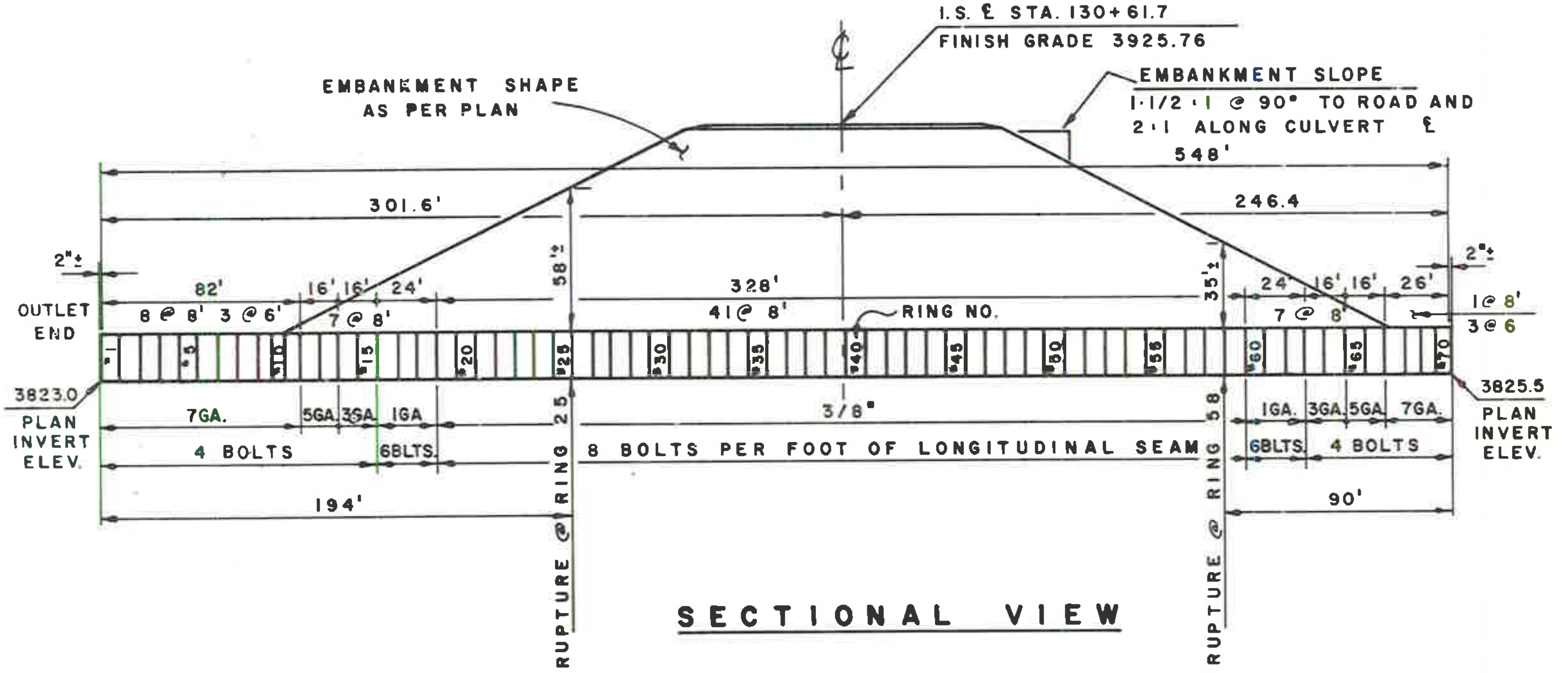

Figure 5. Section through culvert showing plate and bolting requirements.

did show that in laboratory tests their ultimate seam strength did exceed 270,000 lb per lineal ft. Copper-bearing steel was used for the tests and the pipe.

Other features of the 3/8-in. thick plate, such as edge spacing and center to center distances of bolt holes, were the same as the standard for thinner gages. The corrugation spacing was the same as the standard with 6-in. pitch and 2-in. depth. However, due to the thickness of the plates, overlapping plates do not mesh as well as the thinner gages (Fig. 4). Since standard overlapping of plates in fabrication brings 3 plates together at corners, there is an unavoidable 3/8-in. minimum width space at each corner, which permits water to enter or leave the pipe. All bolts and plates used in the pipe were galvanized. Plate lengths of 6 ft and 8 ft were used.

The culvert plates were stepped down from 3/8-in. plates to 1 gage to 3 gage to 5 gage and to 7 gage in thickness at the ends of the pipe where the fill height was less, in order to reduce material cost (Fig. 5). Except for the central portion of the pipe where 3/8-in. plate was used, 1-gage plate was used throughout the pipe in the invert to provide more erosion resistance than would be supplied by the lighter gages of pipe. The bolts used for all except the 3/8-in. plates were 3/4-in. ASTM A 325 bolts.

The special provisions stated that the pipe would not be strutted. It was considered unnecessary and undesirable and was not done during construction. An envelope of granular backfill material was called for to extend from 3 ft under, to 4 ft over the pipe and 12 ft wide on each side of the pipe (Fig. 6). The standard Montana Highway Department specification for backfill material was used, which consists of a granular material usually used for structure and culvert foundations and backfill. This allows a 4-in. maximum size gravel with at least 50 percent passing a No. 4 screen, or a sand, or a combination of sand and gravel. Ninety-five percent of maximum density was required for backfill material ranging from 100 to 120 lb per cu ft.

The special provisions required that the excavation and construction of the pipe be done under dry conditions, i.e., without standing or flowing water in the immediate construction area. The contractor had the option of diverting the stream through pipes, ditches, flumes, or by other means. He chose to use a timber flume. The granular backfill bedding was built up to a highly compacted flat surface upon which the pipe was fabricated. During construction of the pipe and the embankment above it, the contractor was required to maintain traffic through the area since there was no frontage road or other convenient bypass in the area. An impervious clay core completely surrounding the pipe was specified and constructed 42 ft downstream from the inlet.

A placement control device for checking culvert movement during backfill and embankment construction consisted of a plumb bob fastened to a bar hanger on the top inside of the pipe and a location reference assembly on the culvert invert. The latter consisted of a flat steel plate 2 ft sq on which was welded a 3-ft length of 15-in. diameter 14-gage corrugated metal pipe in a vertical position. This pipe was designed to offer protection from water and rocks to a 3/4-in. diameter steel rod also mounted vertically inside the corrugated metal pipe. This rod provided a point reference for the suspended plumb bob. The whole reference assembly was secured to bolts fastened to the invert of the pipe. Fourteen of these assemblies were placed in the middle portion of the culvert at an average spacing of 30 ft apart. This provided a reference to check for rotation or unequal lateral deflection as well as vertical deflection.

Special provisions required that at the stage of construction when the embankment was to a height of 10 ft over the top of the pipe that the vertical dimension of the pipe was to be within plus 6 in. and

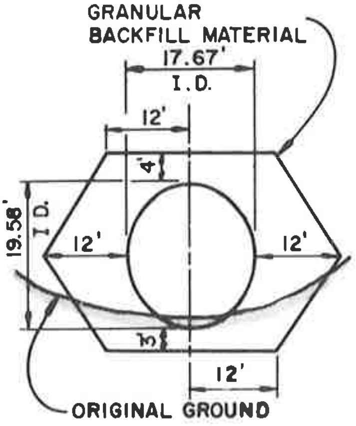

Figure 6. Section of envelope of select material that encased pipe.

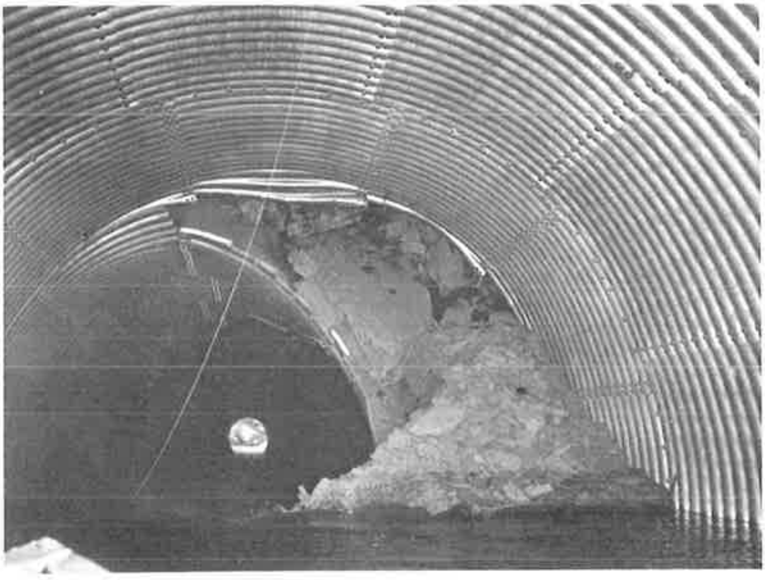

Figure 7. Looking downstream toward failure at ring 58.

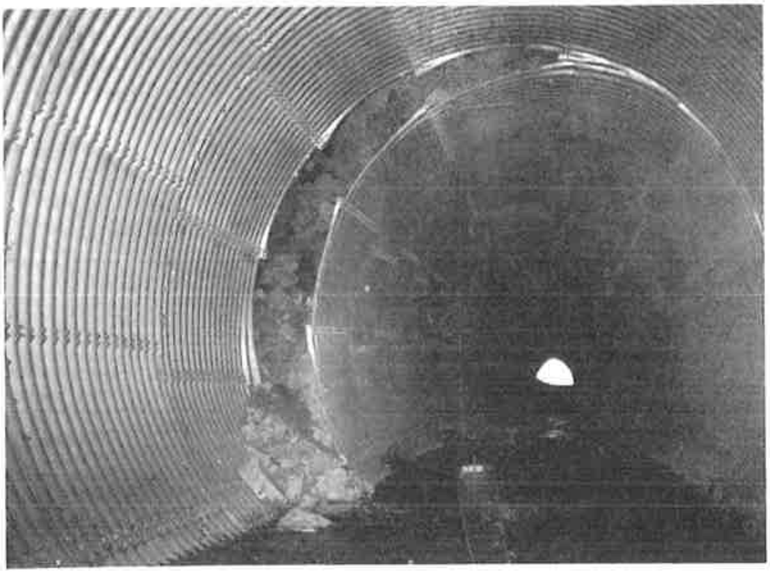

Figure 8. Looking upstream toward failure at ring 25.

minus zero inches of the 5 percent ellipsed shape detailed. Checking at this stage of completion revealed that this tolerance was met. No other deflection measurements were taken after this stage of completion was reached. No other form of deflection control, check, or instrumentation was specified or carried out on this project.

Figure 9. Failure of longitudinal seam allowed plate slippage.

FAILURE OF THE CULVERT

The installation of the culvert began in November 1963, under the construction inspection of the Montana Highway Department. Roadway excavation and placement of embankment over the pipe continued at varying rates through the winter months. Full height of the embankment was reached in early spring of 1964. The second week of June 1964 brought heavy rains and high runoff from the continental divide in the northwestern part of Montana. There were many bridge, highway, and road washouts along with much building flooding in urban areas as a result of the floods. The Little Prickly Pear Creek also had high runoff at this time. However, it was less than the design highwater condition since the large culvert was flowing less than one-half full.

A rupture in the pipe wall was observed from outside the pipe and reported on July 13 by a bulldozer operator who was clearing the creek channel. Subsequent inspection inside of the pipe revealed that two major ruptures and displacements in the circumferential ring seams had occurred. The upstream one was 90 ft from the inlet and occured between the first and second rings of $^3/_8$-in. plate at this end. A lateral displacement of 5 ft had taken place on one side of the pipe at midheight. A large amount of embankment material moved into the pipe through this opening forming a dam 7 ft high inside the pipe causing water to back upstream from the inlet (Fig. 7). A small depression on the surface of the embankment slope was noticeable above this area. The depth of cover over this location was 35 ft. The downstream displacement of 2.4 ft was of the same type, except that a smaller amount of material moved into the pipe and was washed away (Fig. 8). There were 58 ft of fill above this rupture. It also occurred in the $^3/_8$-in. plate between the seventh

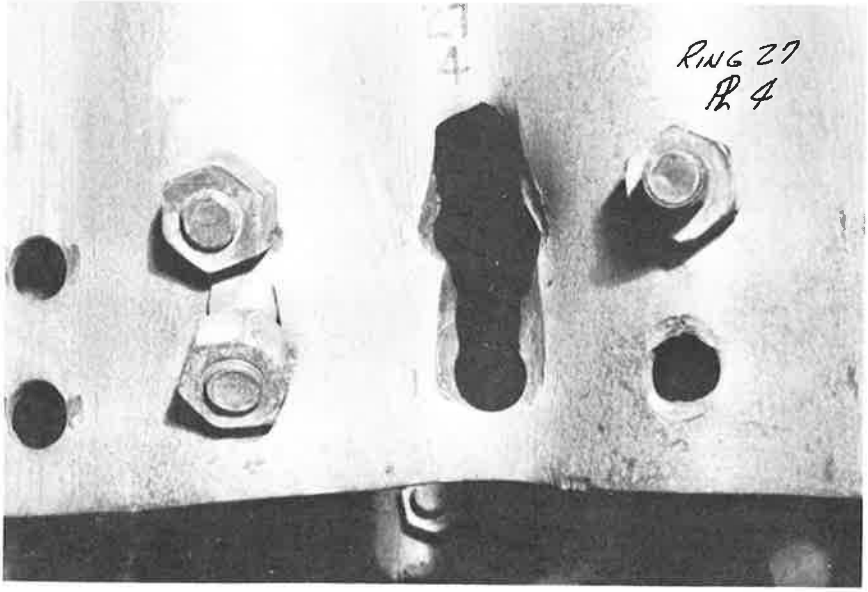

Figure 10. Evidence of plate galling at bolt holes.

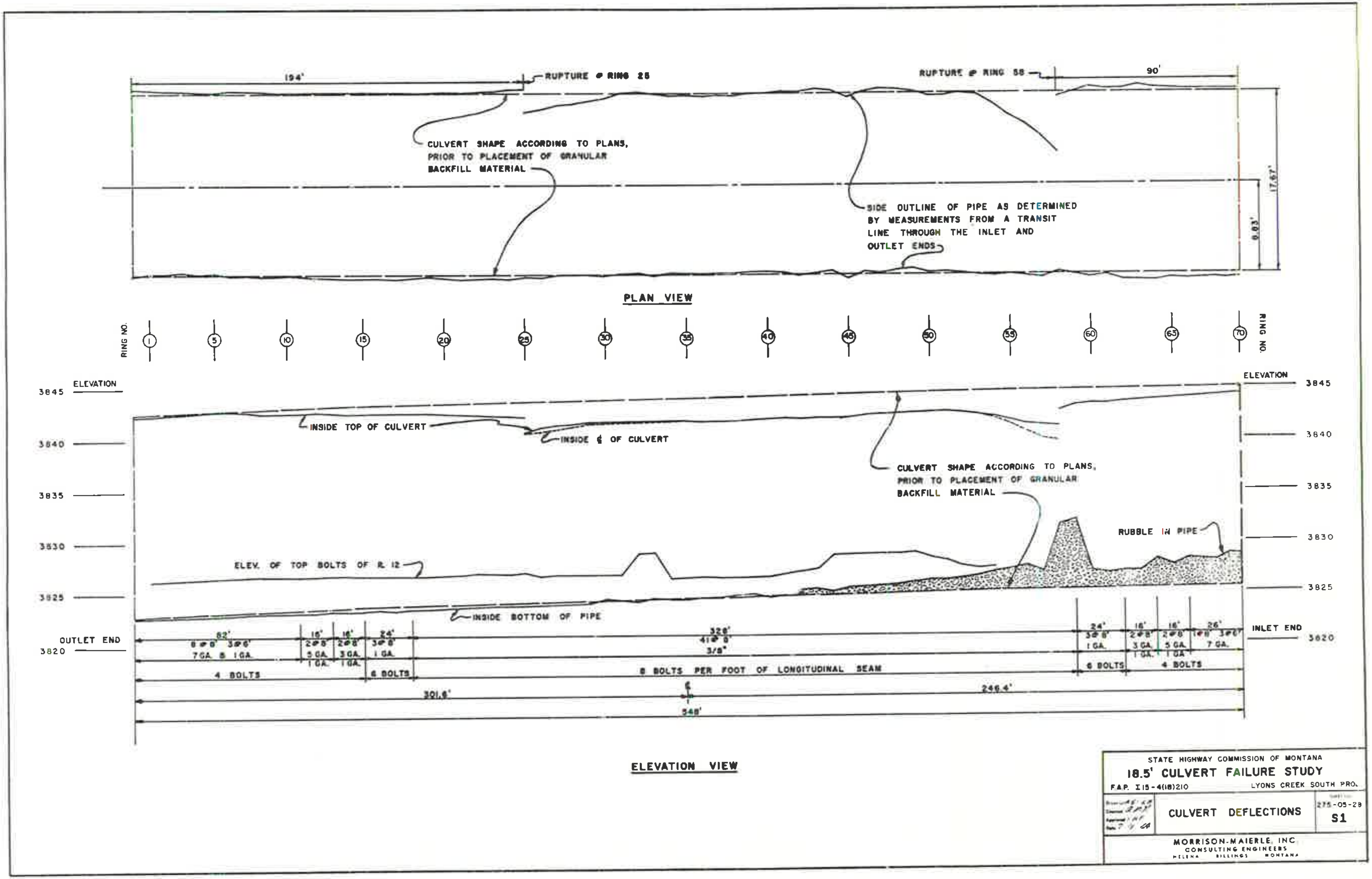

Figure 11. Deflections in pipe after rupture.

and eighth rings from the downstream end of the heaviest plates and 194 ft upstream from the outlet end.

Between the ruptures a longitudinal seam failure had occurred in each ring. The overlapping plates moved past each other 4 to 5 ft, producing a reduction in culvert diameter to 16 ft (Fig. 9). Bolts were sheared and missing not only in the longitudinal seams that had bypassed each other but in other seams that did not have a complete failure. The failure occurred only where the ASTM A 354 bolts were used, which was in all of the $^3/_8$-in. plates. The embankment material above the pipe arched and stabilized because the pipe with ruptured seams would have been incapable of supporting the load had this not occurred. There was no way of knowing how long prior to discovery of the rupture that the failure occurred and whether it was relatively instantaneous or over some period of time (Fig. 10).

A survey crew was immediately assigned to obtain measurements to determine the magnitude of movements. The results showed that the lowest invert elevations were not over a few tenths below the plan elevations of the pipe, which indicated very little settlement had occurred in the subgrade below the pipe. The alignment of the sides of the pipe in plan view showed that they had moved out of position very little except at the locations of the 2 major circumferential ruptures. Most of the extensive failure in the longitudinal joints occurred in the first 2 seams below midheight of the pipe and did not occur consistently on one side of the pipe (Fig. 11).

RECONSTRUCTION OF THE CULVERT

From an evaluation of the available alternates for repair or replacement it was determined that the only feasible operation would be to uncover the pipe. This was done and reconstruction of the pipe has been completed. This included the replacement of damaged plates and replacement of all $^3/_4$-in. ASTM A 354 bolts with $^7/_8$-in. ASTM A 325 bolts. The granular backfill envelope around the pipe was replaced and the bed was shaped to fit the bottom of the pipe to the greatest extent possible. An imperfect trench effect was constructed with baled straw placed over the pipe from 5 ft to 7.5 ft above the pipe and for the full width of the pipe. It extends for almost the full length of the pipe. The embankment material above the baled straw was loosely placed for a height of 6 ft. The placement of embankment to full height was completed in January 1966, and traffic has been using it since then.

Various theories were advanced regarding the cause of the failure. These included penetration and washing of the granular backfill due to high water runoff, vibrations from rerouted trains due to flooded railroad tracks elsewhere, and a mass movement caused by an earthquake or slides in the area. Other more conventional construction factors have been questioned regarding their possible contribution to the failure. These include the magnitude of the adverse influence of using a flat bed instead of a shaped bed on which the culvert was placed, the backfilling and compaction procedures used, and culvert fabrication procedures such as bolt tightening. None of these factors has revealed a conclusive answer to the cause of the failure.

Extensive testing of ASTM A 354 bolts revealed that under a certain combination of environment conditions a phenomenon known as hydrogen embrittlement can occur, which results in reduced strength of the bolts (1). A paper covering this subject as it applies to the ASTM A 354 bolts and bolting procedures used on the Wolf Creek culvert project has been prepared by the Armco Steel Corporation and should be consulted for complete information.

A program to provide checking, testing and control of the culvert and embankment reconstruction has been conducted by the Engineering Department of Montana State University at Bozeman as a research project under the direction of the Montana Highway Department and with the cooperation of the Bureau of Public Roads. The checking and reading of SR 4 strain gages and Carlson soil stress meters used in the control program is expected to continue for some time in order to have the fullest evaluation of culvert stresses and the effectiveness of the imperfect trench used in the reconstruction.

REFERENCE

1. Engineering News Record, Aug. 12, 1965, pp. 126 and 130.