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A Perturbatively NonPlanar SSC at the Ellis County Site

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Summary

Substantial gains in cost and schedule for construction, installation and operation of the SSC at the Ellis County Site can be achieved by the introduction of gentle vertical steering of the beam. Compared to a tilted plane of the sort in the Texas site proposal, the experimental areas and injection regions would be 60 to 120 feet closer to the surface. A specific example is presented and its impacts discussed.

Introduction

The simplest way to design the SSC would be in the horizontal plane, as has been done for most previous accelerators. This orientation would only give one degree of freedom (the vertical elevation of the plane); for the SSC, this would result in parts of the ring being very deep and having to go through layers of less favorable geology.

The next simplest design is to keep the ring in a plane, but with a slight tilt. This option gives three degrees of freedom (e.g., elevation at three points on the ring), with some constraints on slope, total difference in elevation, etc. The LEP ring at CERN is an example (slope of 14 mrad) and the Texas site proposal shows a slope of 3.8 mrad, with tunnel elevation varying from 245 to 585 feet above sea level.

Depending on the site's topography and geology, a nonplanar ring may be advantageous despite the somewhat increased complexity of accelerator design. Additional degrees of freedom can then be used to put the tunnel, experimental halls, and injection/extraction regions at a more optimal depth to reduce construction, installation and operational costs. The Conceptual Design Report (CDR-1986) gives a folded plane as an example (four degrees of freedom). Possibilities for more general configurations are briefly discussed in the Reference Designs Study (RDS-1984) and the Invitation for Site Proposals (ISP-1987).

In designing a nonplanar configuration, the number of degrees of freedom and the constraints (on allowable angles, etc.) are not well defined. The optimal balance of tradeoffs between complexity (largely born by the accelerator physicist) and benefits (largely to the civil engineer, experimenter, and taxpayer) at some point becomes a matter of taste. In this report we consider very gentle departures from a planar configuration,

hence the name "perturbative," with six degrees of freedom and quite small angles. For the Ellis County site, this is sufficient to demonstrate the type of gains that can be made with only a small increase in complexity. It is not an optimal design, but only an example. In addition to optimizing the design at this level of complexity, designs at other levels of complexity could be considered so that appropriate design decisions can be made.

The example described in this note gently steers the beam vertically by small rolls (typically 40 mrad) of the dipole magnets in six sections of the ring, with tunnel slopes of up to 5.65 mrad. Figure 1 locates the effective bend points on the site map. No additional magnets are required and the footprint of the beam in the horizontal plane is taken to be the same as for a simple planar ring. The resulting small amount of vertical beam dispersion is contained within the 7 percent of the ring with rolled magnets. In the example taken here, three of the rolled sections are within the arcs in four-cell modules with 360° betatron phase advance. The remaining three rolled sections are in the near cluster, where the sectional phase advances are 540°. The quadrupoles are not rolled in our example, and the planes are not coupled in first order by this vertical steering.

The bend angles and slopes of the beam for the example described here are quite gentle compared to the terrain following of the SLC or for the Fermilab Main Ring bypasses. Further, the separated-function design of the SSC avoids some of the problems encountered in the SLC. Thus, the difficulties encountered in commissioning and operating these machines due to their nonplanarity should be far less (or nonexistent) for perturbative SSC designs as discussed here.

To summarize the gains made by this example, beam at the experimental halls and injection straight sections in the near cluster would average about 90 feet deep instead of about 160 feet deep with a tilted plane similar to that proposed by Texas (but obeying the 35-foot-minimum-depth rule). This choice would ease both the construction and operation of these experimental facilities and the injection system. The average depth of the tunnel at the far experimental halls would also be about 90 feet for the example given here, a considerable improvement over the 190 feet depth for the tilted plane. The average depth of service area shafts is about 50 feet less deep for our nonplanar example than for a tilted plane with 35-foot minimal depth, typically 115 feet deep instead of 165 feet. A net savings of about $36M (FY 1988 $) is estimated for the civil construction of 4 experimental halls plus the tunnel and service area shafts, including A-E/CM work and contingency (about $44M in then-year $). Additional savings would come from the injector systems and the construction of additional experimental halls. Harder to estimate are the substantial installation and operational savings, both in time and money.

Example PNP Design

As an example of a perturbative nonplanar (PNP) ring for the Ellis County site, we consider the solution shown in Figure 2. It contains six vertical bend points, listed in Table I; point A is the center of the near cluster. The change in slope at the bend points is typically 3 mrad, requiring dipole rolls of about 40 mrad over about 1 km. Less than 8 percent of the dipoles are rolled in this example. The centerline of the tunnel varies from 375 to 633 feet above sea level, with the maximum slope of the tunnel being 5.65 mrad.

The depth of the tunnel center line at each of the service areas and for the eight straight sections (experimental halls and injection areas) is shown in Table II, for both the Texas proposal (tilted plane) and our PNP solution.

The PNP solution was developed using the large scale Tunnel Profile drawing provided as Exhibit 3.2.2-1 from Appendix A of the Texas proposal, reproduced here as Figure 3. (Note that the circumference of 53.6 miles shown by this figure assumed the tunnel to be in the center of the 1000-foot wide strip and is slightly larger than the value of 53.25 miles used in Table I.) A minimum depth for the tunnel centerline of 35 feet was taken, as given by the ISP (Invitation for Site Proposals, DOE/ER-0315, April 1987). The tilted plane shown on this drawing, used for the "TX" depths in Table II, does not satisfy this criteria, in particular being only about 12 feet at Waxahachie Creek near E2. Lowering the tilted plane at this point to satisfy the 35-foot rule would increase the average service-area depth by about 12 feet and the depth at the near cluster by about 19 feet.

Several issues must be addressed before the final ring profile is chosen, whether planar or nonplanar. The ISP states that fee simple title to the land is needed for these regions in which the depth is less than 50 feet. A greater depth would also help to damp out vibrations from road and rail traffic. A 50-foot minimum in the arcs may thus be a preferred policy. For the PNP solution shown here, roughly one mile of the arcs lies between 35 and 50 feet deep (regions near mile 8, 16, and 47) and this would require acquisition of about 120 acres in fee simple in place of stratified fee. The exact amount would depend on a more careful survey and study of the local topology. Another consideration is to keep tangents drawn to the ring underground for a minimum distance (roughly 2 miles) to range out most muons in case of inadvertent loss of beam (minimum distance for the PNP example is 2.7 miles). Another issue is the minimum safe depth below Bardwell Lake near F6; this will depend on the local fault lines in the Taylor marl.

Impact on Civil Construction

Costs

A rough cost comparison was made for the PNP example and the tilted plane in the Texas proposal using unit costs (FY 1988 $) developed for the Life Cycle Cost (LCC) estimates.

Raising the tunnel places an additional 4.5 miles in the Taylor marl (instead of the Austin chalk). For an additional cost of tunneling of $250/foot in the marl, this amounts to an additional cost of about $6M for the PNP solution. Some (or all) of this may be offset by avoiding the Eagle Ford shale in the near cluster region.

The costs for shafts were estimated as $4.9K/foot depth for the 20-foot diameter "E" shafts and $10.8K/foot depth for the 30-foot diameter "F" shafts. The decreased depth results in a savings of about $6M; this value may be an underestimate in that costs increase with depth. An additional saving of about $0.7M comes from a reduction of shaft spoils needing disposal.

The big savings come from the more shallow experimental halls. Four halls, each 260' long by 90' wide by 80' high were assumed, all cut and cover construction. For the near cluster, the K1 and K2 alternate positions were assumed with a cost of $10.4M for each of the PNP cut and cover halls, a savings of $7.3M each over the underground cavern construction assumed in the LCC. For the halls at K3 and K4, the savings were found to be $3.8M per hall, with a factor of three less material having to be excavated in the PNP case. The savings would be even greater if similar halls were installed at the deeper K5 and K6 locations (225 feet to the beam for the planar case, compared to 110 feet for PNP).

The net direct savings for the above is about $23M (FY 1988 $); including the A-E/CM at 16 percent, management and support at 10 percent, and contingency at 24 percent, boosts this value to $36M (FY 1988 $). In then year (as spent) dollars a savings of about $44M is obtained. This sum is a minimum in that substantial additional savings would be realized if six, rather than four experimental halls are constructed. Also, not considered here is the cost saving for the injector system; we must await a conceptual design for the optimal depths of the injector accelerators for the PNP and planar examples. The smaller volume of material excavated (especially for the cut and cover experimental halls) makes for less environmental mitigation required. This situation and other "ripple" effects from the shallower depth will also add to the cost savings, and a bottoms-up type of estimate may be needed to establish the full cost savings possible.

Reduction of Uncertainties

The added flexibility allowed by the PNP method can be used to minimize the inherent uncertainties associated with underground construction. The tunnel can be raised to avoid the Eagle Ford shale in the NW sector of the ring. The example chosen appears to avoid the chalk/shale interface with room to spare, whereas a planar ring obeying the 35-foot rule on depth appears to be at or very close to the interface over about 4 miles. The PNP foundations for experimental halls at K1 and K2 would be solidly in the Austin chalk, not the more problematic shale. With somewhat stronger bending than used in the example, an additional 20 feet or so of elevation could be gained in this region should the more detailed geotech studies indicate the need (the minimum muon range would have to be closely watched in this case). Hollowing out of caverns for the experimental halls would not be required and a greater flexibility and size for the underground halls and assembly areas would be possible. In particular, the spans would not be limited by questions of rock competency necessary for a stable ceiling over the detectors.

Schedules

The reduced depth of shafts will clearly help to speed the tunneling effort. Cut and cover construction (in lieu of caverning) for certain of the experimental halls can utilize standard earthmoving equipment and methods. This offers the probability of reducing construction time significantly compared to that needed for caverning. The greatly reduced amount of material needed to be moved for the shallower halls would expedite their schedule as well; a detailed site-specific analysis is needed to determine actual gains. Beneficial occupancy of the experimental halls is likely to be on the critical path and early occupancy will clearly be crucial to having properly functioning detectors ready on time.

Surveying

Survey and alignment will be a challenging task, whichever vertical profile is taken. While conceptually simpler than the PNP method for the accelerator designer, the tilted plane is actually more complex as viewed locally by the surveyor.

Even for a horizontal plane, the magnets will appear locally to have a roll (from the direction of local gravity) due to the earth's curvature, varying from 2.3 mrad (arc centers) to 1.9 mrad (cluster centers). This complication will apply to both the tilted plane and PNP, but for clarity we will ignore it from here on. The tilted plane in the proposal has a slope of 3.82 mrad (0.22°) and the magnets have a roll varying as $\cos\phi$ around the ring (ϕ is an azimuthal-type angle starting at zero near F1), from +3.82 mrad

near F1 to -3.82 mrad near F6. Note that the roll of each magnet is (slightly) different from its neighbors. For the PNP example, the roll is zero for 3554 of the dipoles and at the six values listed in Table I for the remaining 294 dipoles.

The slope of the tunnel varies continuously around the ring for the tilted plane with a $\sin\phi$ dependence. For the PNP example, 93 percent of the tunnel is in segments of constant local slope. In fact, a 19-mile stretch (36 percent of the total ring) is horizontal with zero slope.

Cryogenics

The total difference in elevation around the ring is 340 feet for the tilted plane and 260 feet for the PNP example. The total difference in hydrostatic head around the ring is thus similar for the cryogenics in the two cases, though slightly better in the PNP case. The PNP local slope is larger by 1 or 2 mrad than the 3.82 mrad of the tilted plane, however, over 7 percent of the ring. Both cases must allow for a change of hydrostatic head and there appears to be little difference in impact on the cryogenics.

Impacts on Installation and Operation

One of the subcriteria used for site evaluation was, "Installation and operational efficiency resulting from minimal depths for the accelerator complex and experimental halls." The Texas site was better than several of the other finalists in this regard and received a rating of "good."

The more shallow depth afforded by the PNP method would obviously improve these efficiencies, though it is difficult to quantify the cost and schedule savings without a detailed set of scenarios. In some areas, the most important advantage may come from allowing a totally new method of operation, such as the transport of magnets and detector subassemblies by vehicles down a ramp rather than by crane. Such ramps would be used during construction of the experimental halls and could be made permanent. The use of ramps could simplify the magnet support design by no longer requiring the magnets to withstand a near vertical orientation while being lowered to tunnel depth.

Cut and cover for the collision halls offers flexibility in the design of other nearby underground facilities such as bypass tunnels, assembly halls, control rooms, etc. This flexibility could be used to improve installation and operational efficiencies. Being closer to the surface should also help to minimize the type of logistics bottlenecks experienced by LEP and would provide savings in calendar time, especially for the assembly of large detectors.

Operational maintenance of both accelerator components and detectors would also be eased by the more shallow PNP configuration. It would also make emergency access and egress somewhat easier -- typically ten stories worth of stairs instead of 15 or 20.

Impacts on the Collider Accelerator Design

The simplest way to think of the PNP design in first order is to consider the accelerator to be in the horizontal plane and to treat independently the vertical steering. In the example chosen, the horizontal footprint stays the same and the transverse (betatron) motions of the protons remain decoupled because the quadrupoles are not rolled (unlike the elegant folded-plane example in the CDR).

Rolling the bending magnets gives a cheap way to get horizontal field for the needed vertical steering, $B_H = B_o \sin\phi$. The main vertical field is, of course, diminished slightly, $B_V = B_o \cos\phi$. For the very gentle solution taken here with a typical roll of 40 mrad, the loss is about 0.08 percent or 1.05 Tm per cell. This could be made up by using about one third of the horizontal trim magnet strength, or, by selecting dipoles on the high side of the magnet transfer function (B/I). For an rms variation of $\pm$ 0.03 percent, as given in the CDR, about 9 percent of the magnets will have B/I at least 0.04 percent high; using these magnets in the rolled sections would actually help reduce the overall rms deviation from the desired values. More sophisticated solutions such as changing the horizontal geometry slightly also exist. In any case, it's not a problem, and could even be useful.

The method chosen confines the vertical dispersion introduced by the vertical steering to the 7 percent of the ring where the steering takes place. In the arcs, this is done by rolling all dipoles by the same amount over a 360° phase advance (4 cells = 917m = 0.57 miles). Vertical bending in the cluster regions is achieved in a similar way, by rolling the bending magnets that are used to decouple the long straight sections. The insertions used between long straight sections suppress the horizontal dispersion to zero at each end. The asymmetric optics of the two rings guarantees that the vertical dispersion (caused by rolling all bends by the same amount) is also suppressed. The vertical dispersion in the bend regions typically reaches 0.24m for a 40-mrad roll (8 percent of the horizontal dispersion) through four arc cells. The effect of this dispersion is quite small, $\pm$ 12μm for $\sigma_p/p = \pm 0.5 \times 10^{-4}$ at 20 TeV, compared to the normal beam size from betatron motion of 130 μm or the expected corrected closed orbit distortions (rms value 380μm in the arc quadrupoles).

At injection, there is a large systematic normal sextupole component in the dipoles, about 8 units (10^{-4} at 1 cm) due to persistent currents. A roll of 40 mrad results in a skew sextupole of 0.32 units, to be compared with the expected rms variation of $\pm$ 0.6 units. To first order, effects such as this skew sextupole cancel when summing over a 360° phase advance.

Some cancellations presumably also occur in the cluster regions. Depending on the correction scheme adopted, such effects may be even more reduced locally, for example, by distributed bore tube correction coils.

As for any accelerator design, many details must be done correctly, often to an exceedingly high precision. Nonplanar designs do add some complications, which while minor, must be properly handled. For example, if we keep the same horizontal profile, the additional circumference caused by the cosine of the finite slope is an additional 27 cm. This value must be adjusted to zero or taken into account in designing the injector system.

A more subtle and trickier effect is that the vertical separation (70 cm) of the beams in the regions of vertical steering, interlaced with the crossing of the beams in some of the straight sections, introduces a change in circumference of 2 to 7 mm for our PNP example, depending on where the beams cross. For example, a 6.28 mm difference in circumference could be accommodated by running the two beams $\pm$ 0.5 mm on average off the nominal closed orbit. While this is a small fraction of the usable aperture, the circumference difference could be corrected in other ways in the final design.

We leave to the experts consideration of methods that might be used to preserve beam polarization should that be desired.

Remarks

The mention of nonplanar schemes generates a negative reaction on the part of many accelerator physicists. Yes, it does complicate an otherwise beautiful and elegant design. Unfortunately, engineering trade-offs often do intrude and introduce complexity in the real world. While the experience with terrain following for SLC and bypasses for the Main Ring has not been the happiest, the amount of vertical bending, slopes, etc., are much reduced for the example discussed here by factors of typically 5 to 10. In addition, the SLC case was made tremendously complicated by the strong combined-function magnets, and the Fermilab Main Ring designers had to deal with an existing machine with little space or flexibility.

Given the perturbative nature of the example discussed here, the detailed set of beam diagnostics and sophisticated computerized correction schemes anticipated, one might expect that commissioning such an accelerator should not be much different from that for a planar machine.

Questions and Issues

- What gains can be made by optimizing and improving upon this example?
- What is the optimal balance between complexity (number and strength of vertical bends) and gain in flexibility? Some additional examples would be useful.
- What are reasonable limits on roll angles, tunnel slopes, etc.?
- What is the minimal acceptable muon range?
- Should we avoid taking fee simple in the arcs by holding to a 50-foot depth?
- What is the optimal depth at the experimental halls and injection regions?
- What is the minimal depth beneath Bardwell Lake?
- Where is the shale and how bad is it?
- What are the environmental advantages and disadvantages relative to alternative designs?
- What is the real cost advantage including the injector, additional experimental halls, etc.?
- What are the gains in schedule, installation and operational efficiency, etc.?
- Is it worth it? $44M (or more) would go a long way in upgrading a present-day detector, or improving beam diagnostics and controls, or providing more and larger experimental areas, or . . . .

Table I. PNP Example Bend Points and Slopes

Point	s (miles)	y (feet)	$\Delta\alpha$ (mrad)	ϕ (mrad)
A	0.00	625	-3.60	-44
B	1.42	633	-3.37	-41
C	22.71	375	+2.30	+29
D	42.50	375	+3.95	+50
E	49.55	522	+1.70	+22
F	51.83	590	-0.98	-12
A	53.25	625	-3.60	-44

Segment	Δs (miles)	α (mrad)
AB	1.42	+1.07
BC	21.29	-2.30
CD	19.79	0.00
DE	7.05	+3.95
EF	2.28	+5.65
FA	1.42	+4.67

s - clockwise distance around ring, starting at point F10 (middle of near-side cluster)
y - elevation of tunnel centerline above sea level
α - slope of beam and tunnel (+ for increasing elevation in clockwise direction)
$\Delta\alpha$ - change of slope
ϕ - magnet roll

TABLE II. DEPTHS AT SERVICE AREAS AND EXPERIMENTAL HALLS

Minor Service Areas

	D(TX)	D(PNP)	ΔD
E1	120	90	-30
E2	100	120	+20
E3	140	160	+20
E4	130	120	-10
E5	180	130	-50
E6	230	110	-120
E7	220	110	-110
E8	160	100	-60
E9	100	90	-10
E10	110	100	-10
Total	1490	1130	-360
Average	149	113	-36

Major Service Area

	D(TX)	D(PNP)	ΔD
F1	140	150	+10
F2	180	210	+30
F3	80	90	+10
F4	130	100	-30
F5	200	100	-100
F6	220	100	-120
F7	200	110	-90
F8	150	140	-10
F9	90	80	-10
F10	150	80	-70
Total	1540	1160	-380
Average	154	116	-38

Experimental/Utility Areas

	D(TX)	D(PNP)	ΔD
K1	170	110	-60
K2	180	130	-50
K3	150	80	-70
K4	160	70	-90
K5	220	110	-110
K6	230	110	-120
K2(Alt.)	110	70	-40
K1(Alt.)	120	60	-60
Total	1340	740	-600
Average	168	93	75

TX: tilted plane given in Texas proposal (12-foot minimal depth)
PNP: example used in this report (35-foot minimal depth)

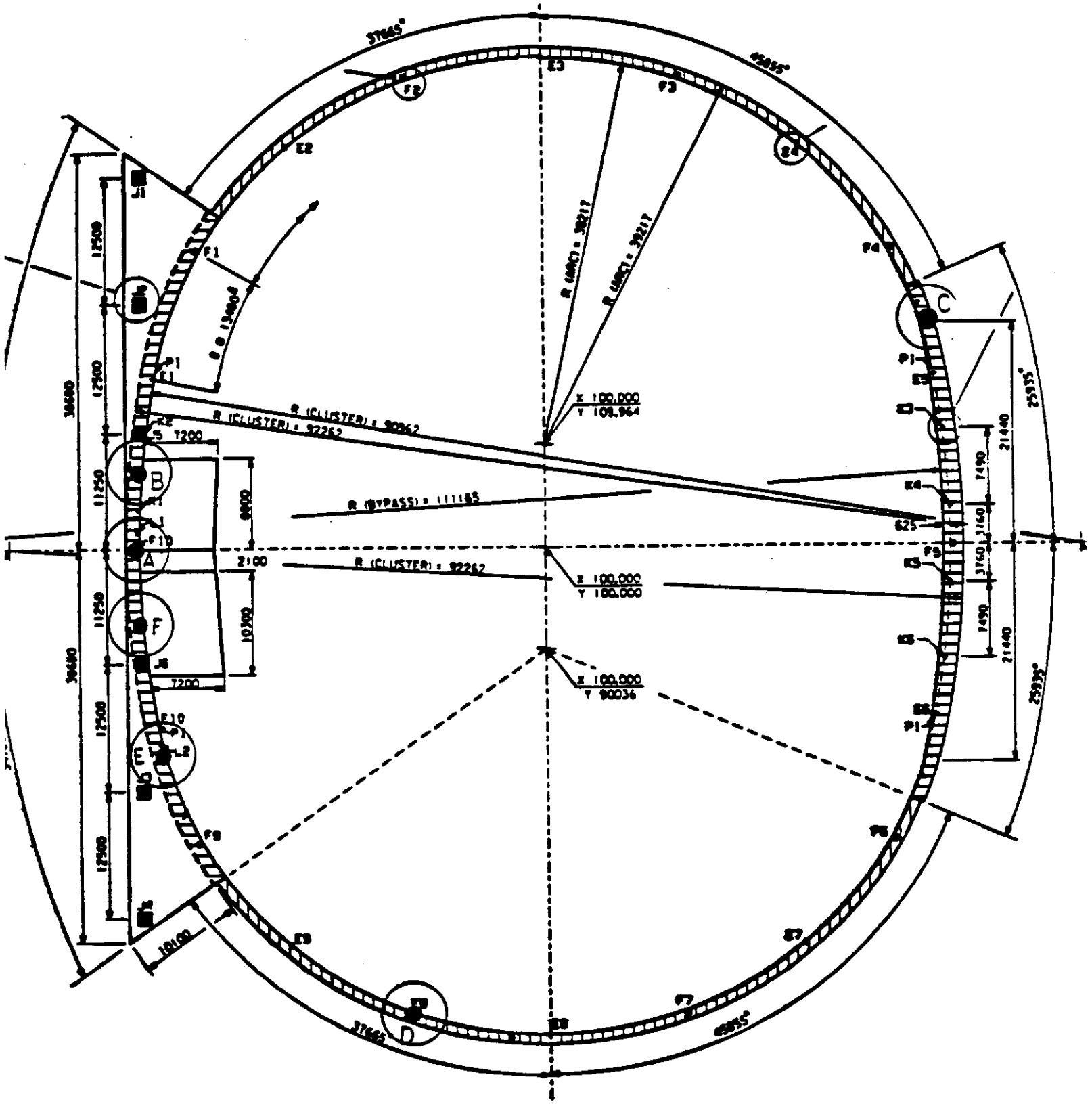

Figure 1 PNP example vertical bend point locations.

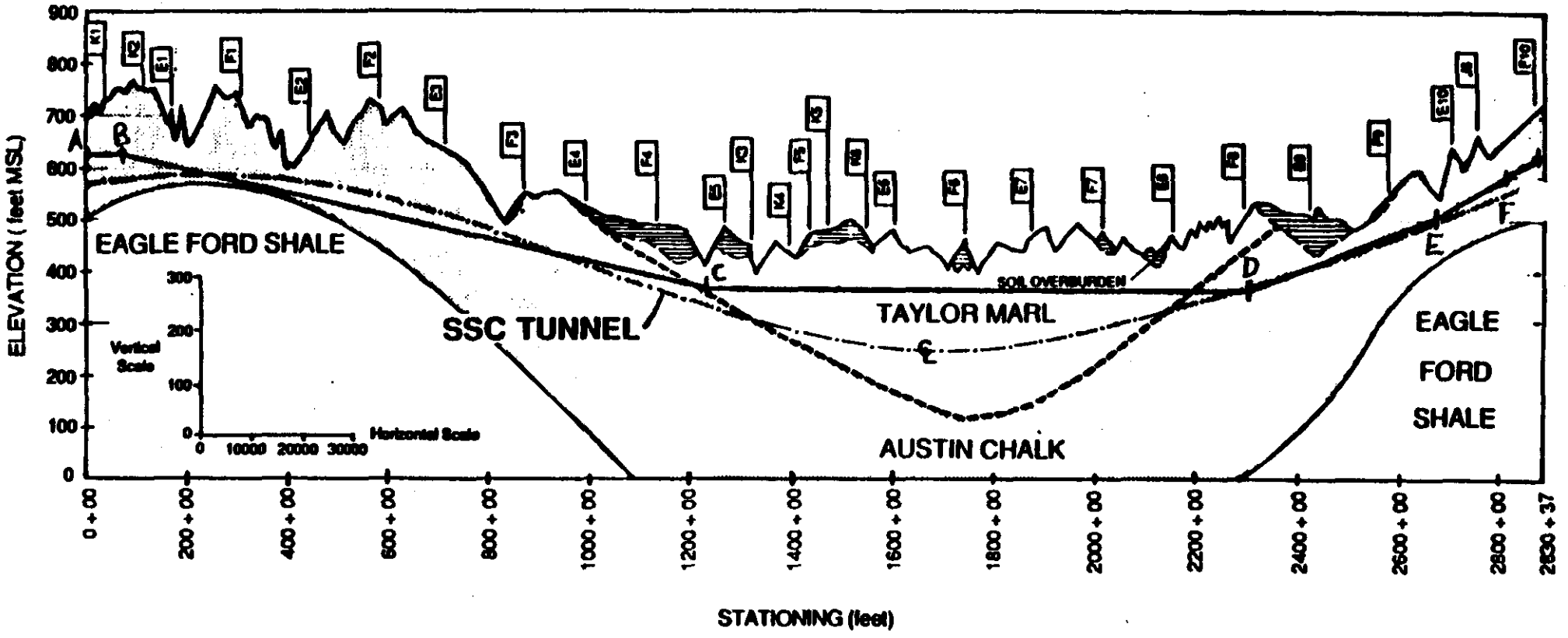

Figure 3.1-2. Geologic Profile Along Collider Ring. The SSC ring will be almost horizontal in the favorable Austin Chalk and Taylor Marl.

Figure 2 Sketch of Perturbative NonPlanar example with bend points A through F.

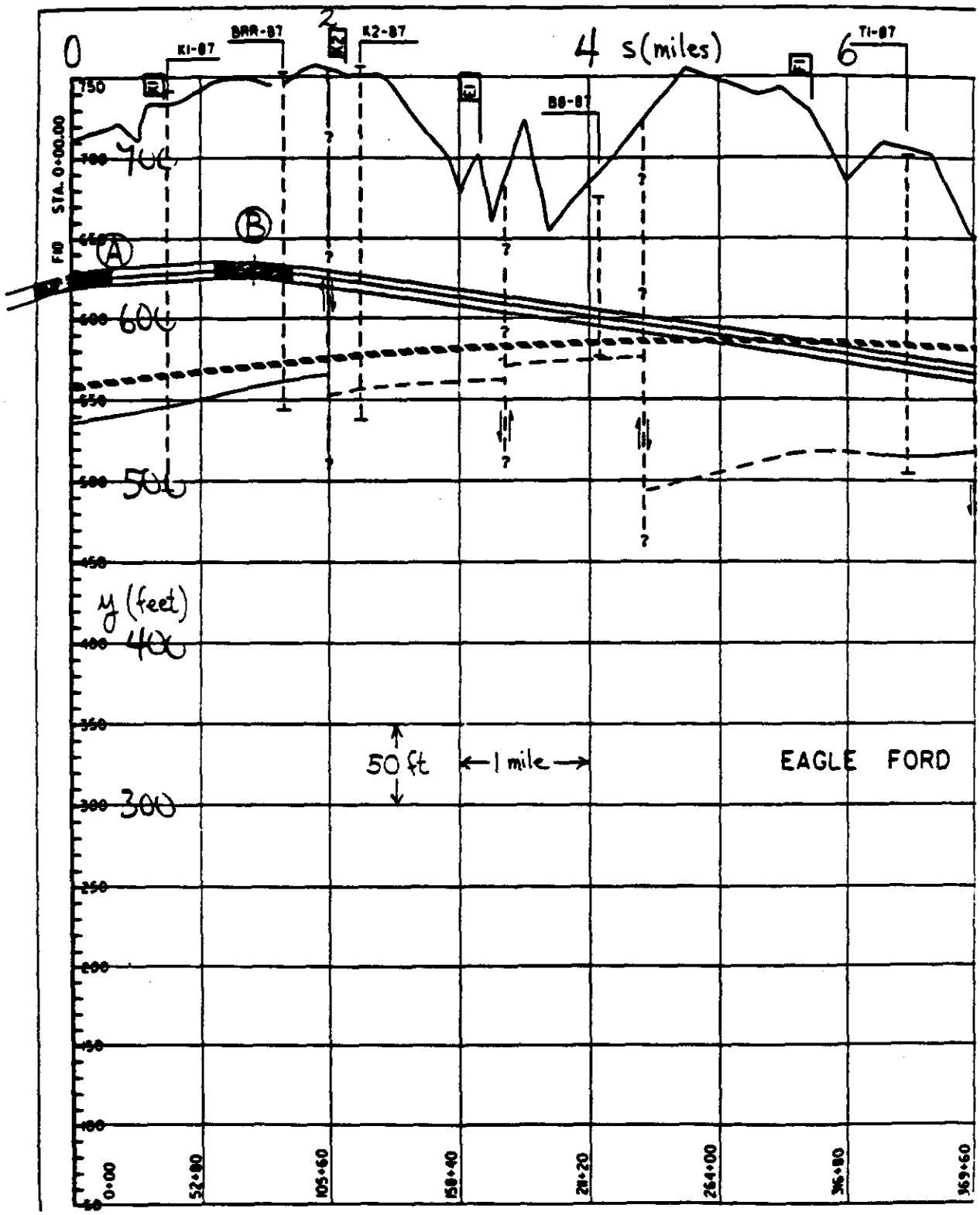

Figure 3a
Tunnel Profile from
Texas Proposal.

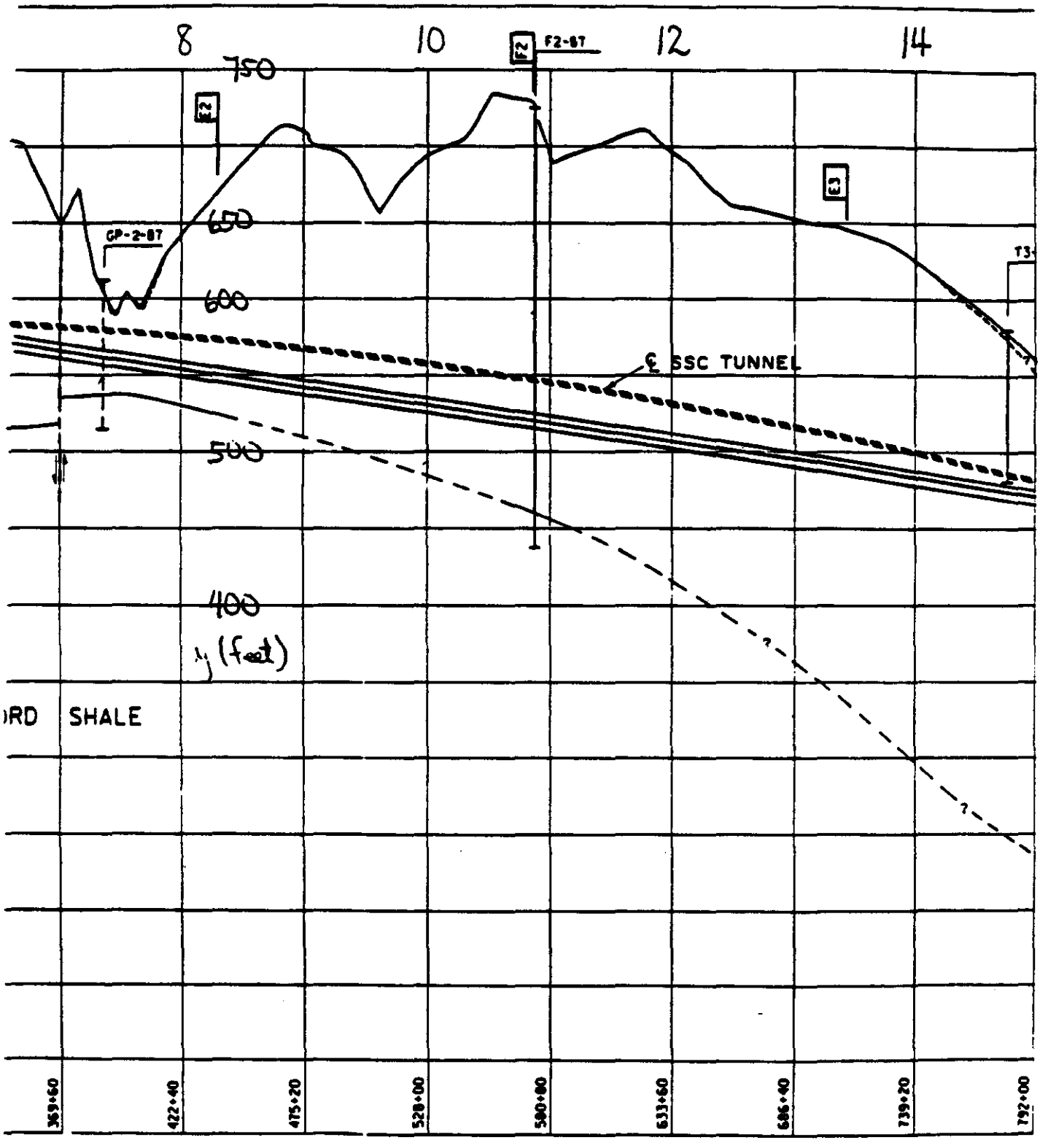

Figure 3b
Tunnel Profile from
Texas Proposal.

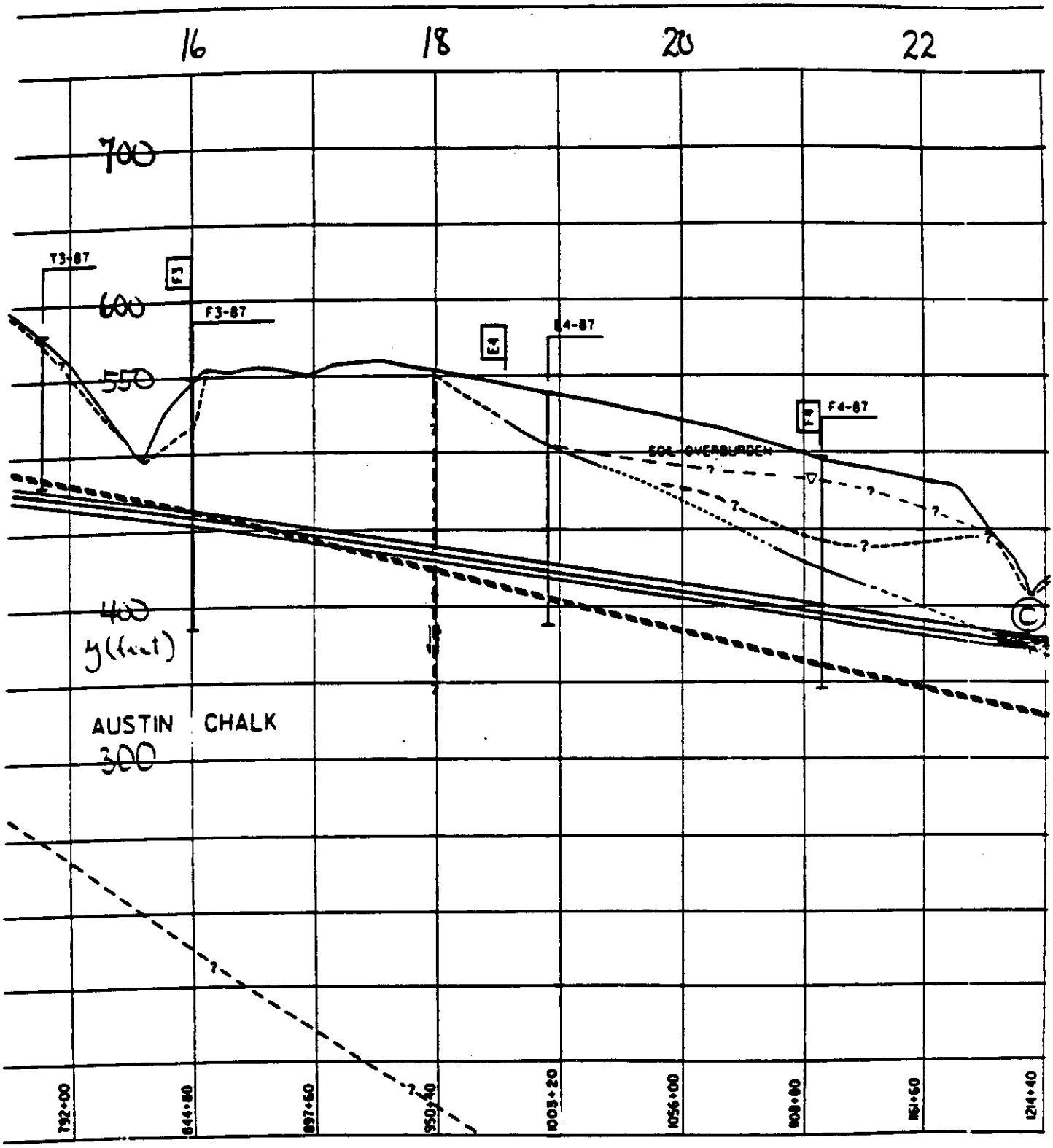

Figure 3c
Tunnel Profile from
Texas Proposal.

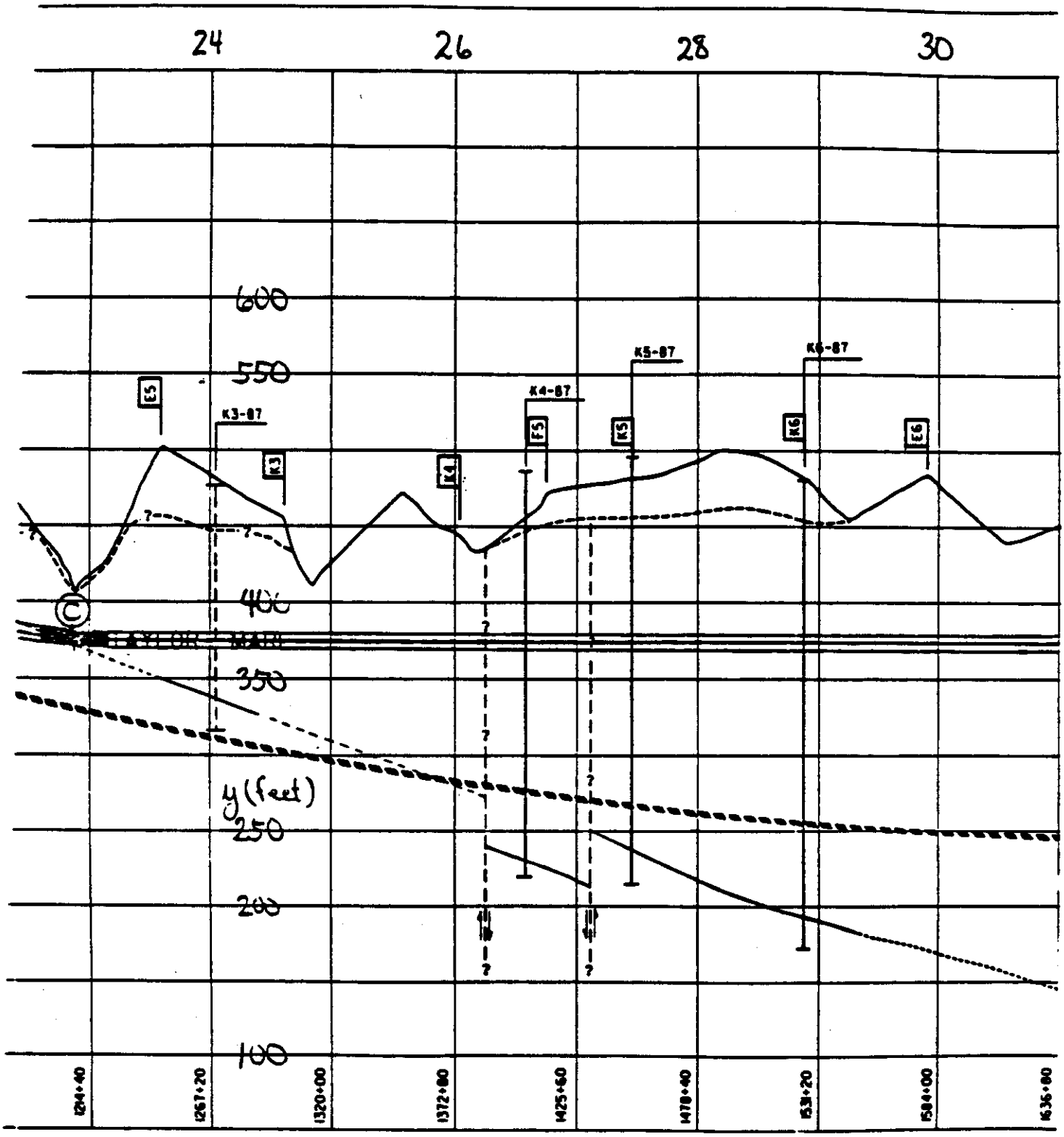

Figure 3d
Tunnel Profile from
Texas Proposal

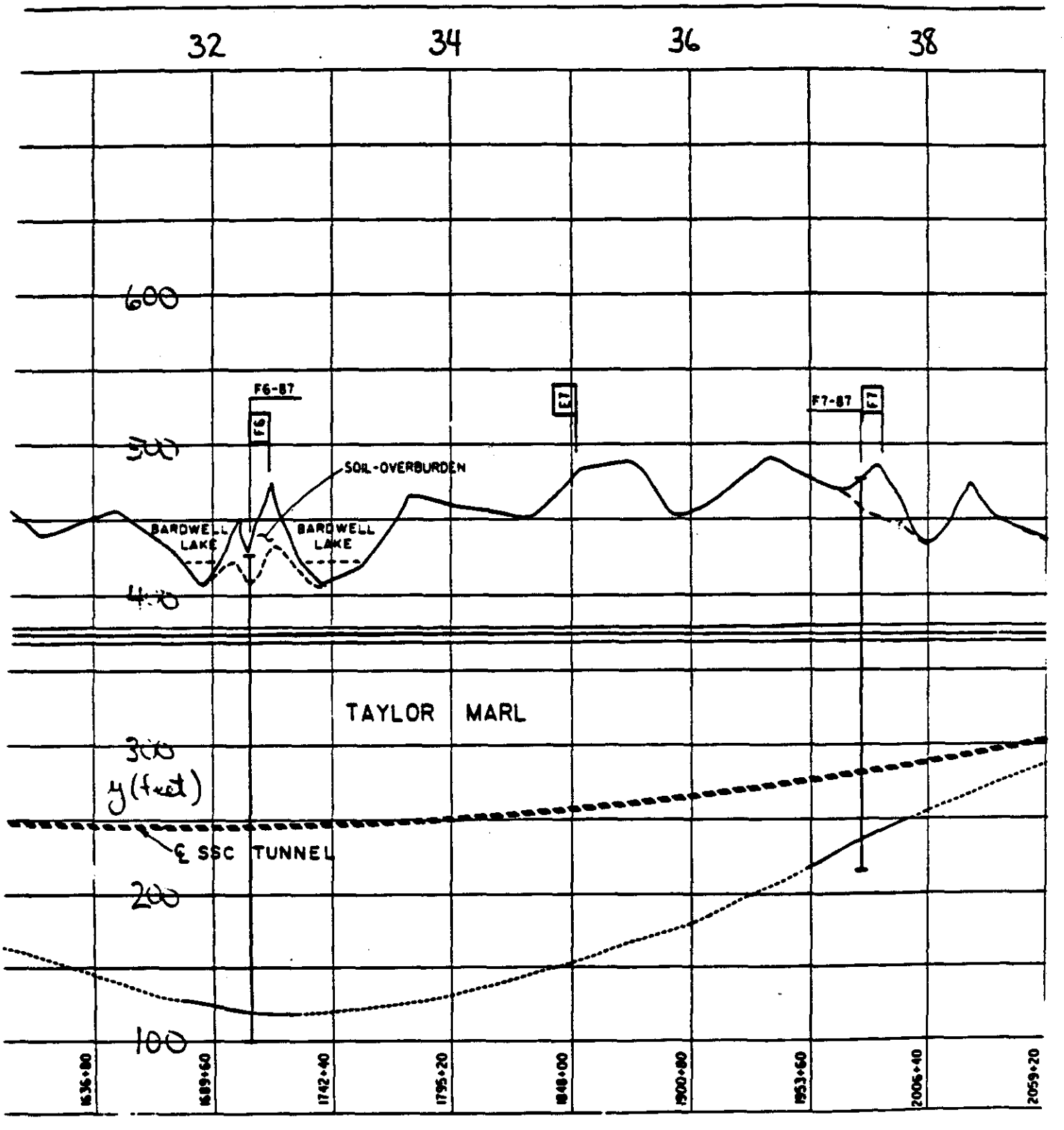

Figure 3e
Tunnel Profile from
Texas Proposal

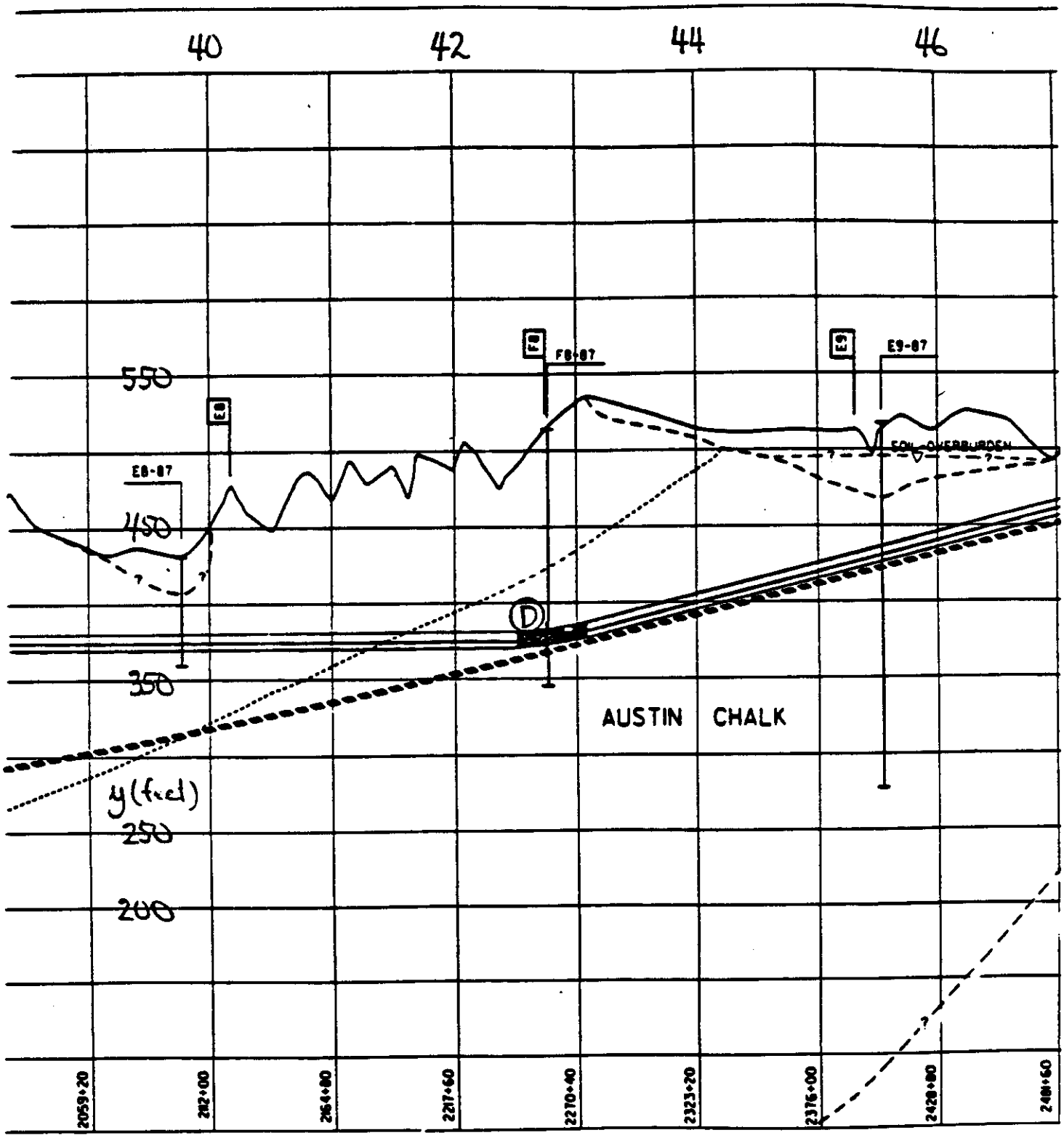

Figure 3f
Tunnel Profile from
Texas Proposal

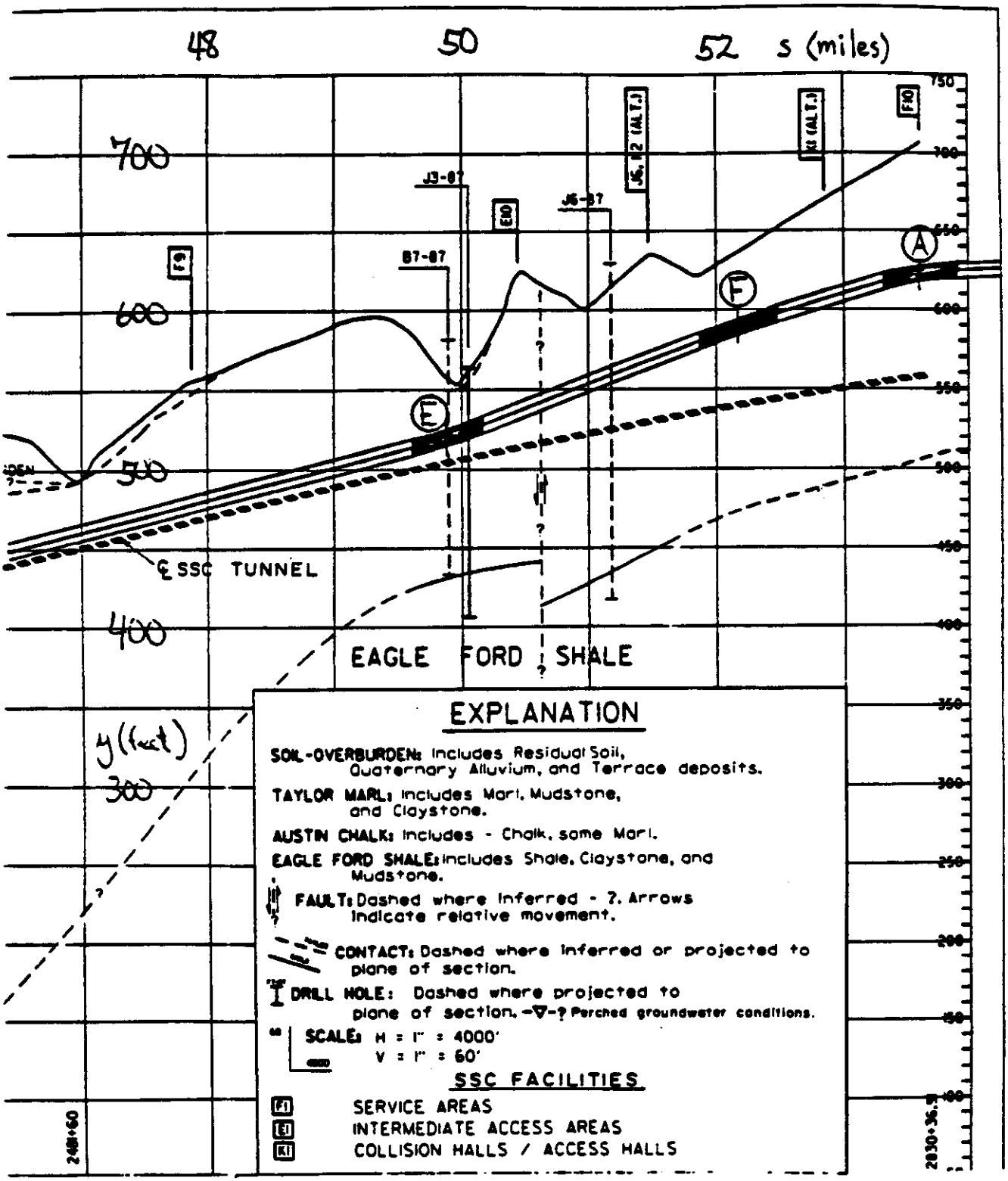

Figure 3g
Tunnel Profile from
Texas Proposal