Inertial Forces from Earthquakes on a Hyperloop Pod

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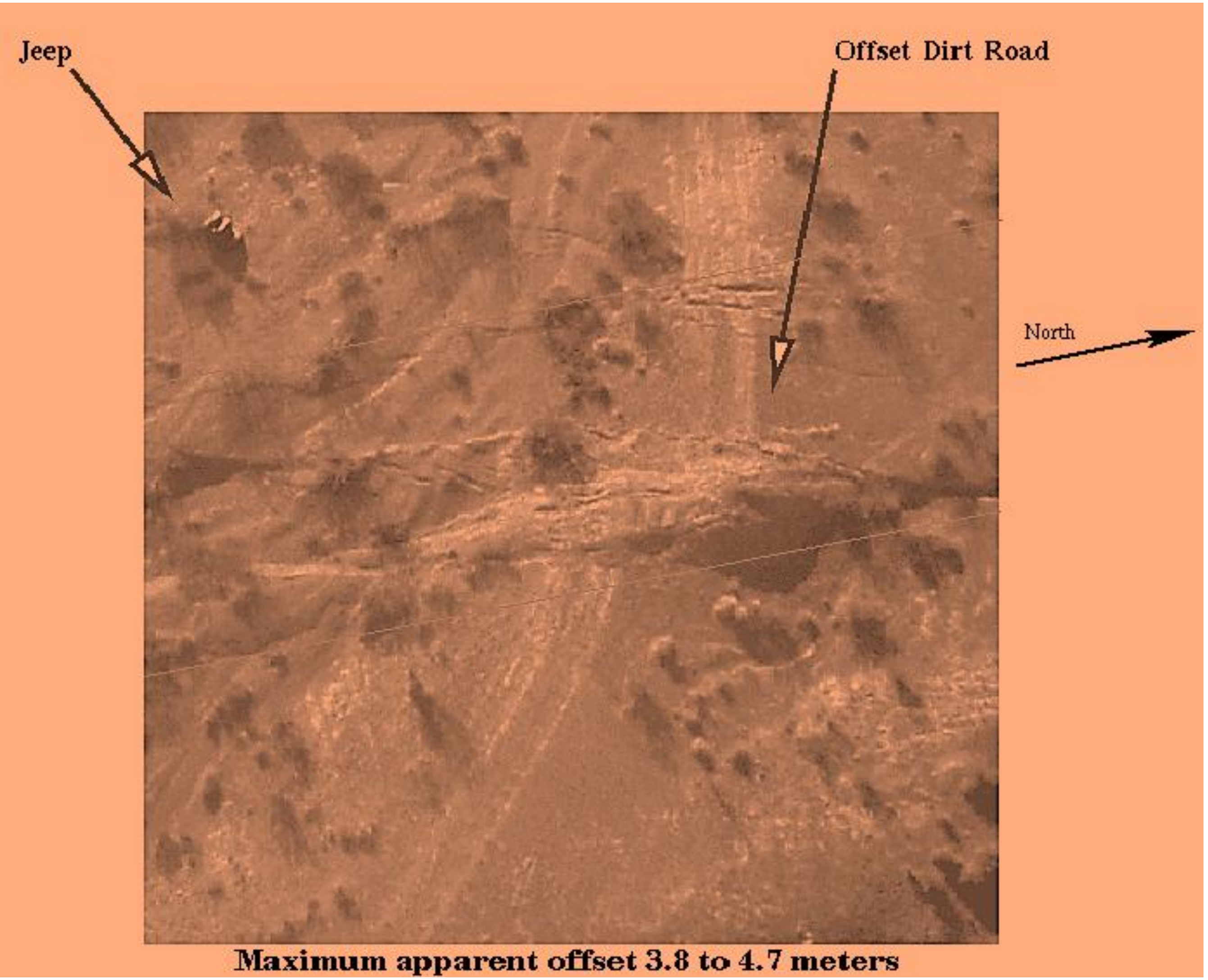
350 m/s in a steel tube during an earthquake… what could possibly go wrong?

- Fault slippage might rupture the tube 
- Not a good idea to cross a fault underground  
- If the tube does not rupture, can the deformation be distributed to **limit the lateral acceleration** of pods?
- Even without a fault crossing, the shearing in seismic waves will bend the tube; what is the lateral acceleration due to this shearing?
- The tube will sway laterally when shaken; what accelerations happen when a pod shoots through a swaying tube?
- I suggest a clever control mechanism to mitigate this problem

1991 M 7.1 Landers earthquake

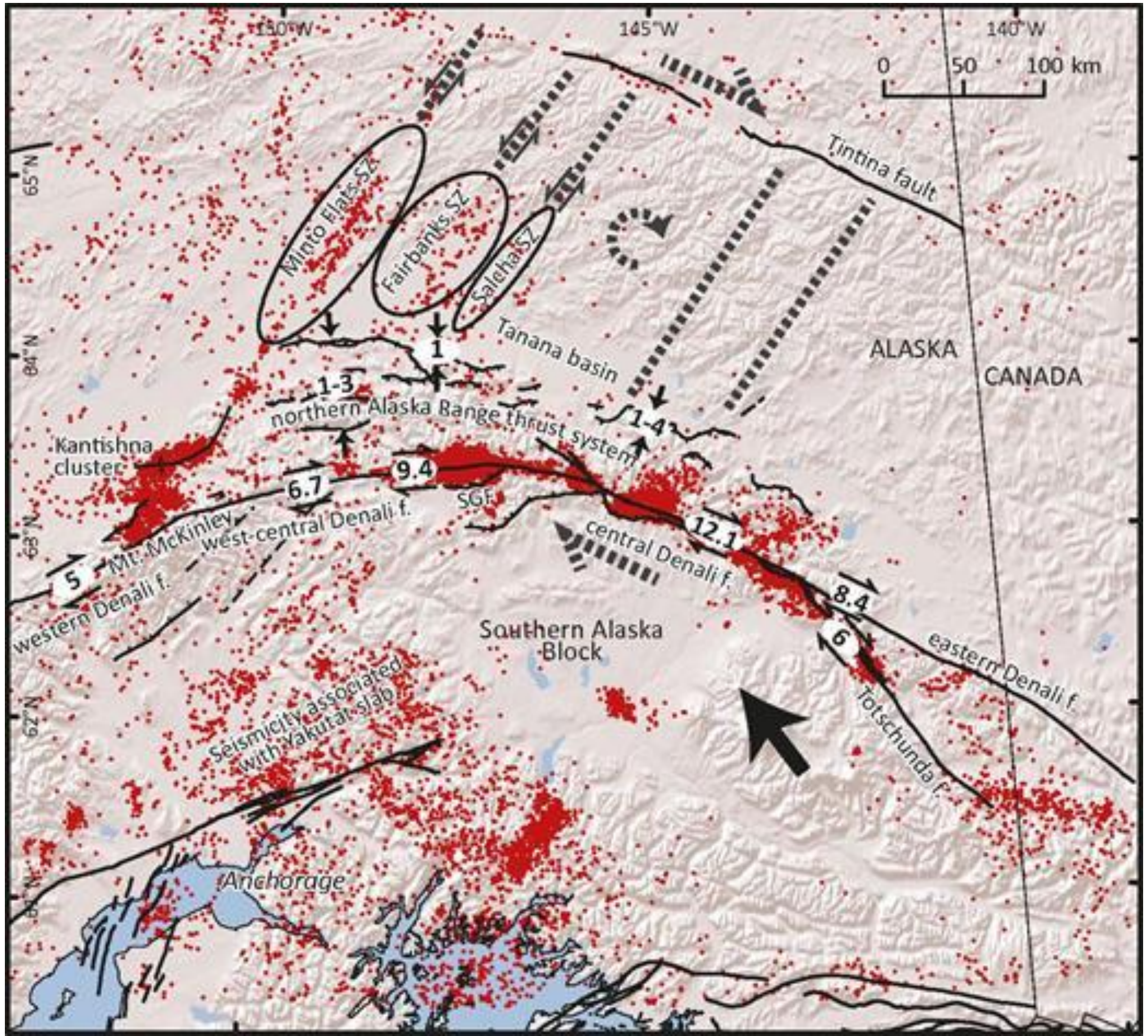


- Previously unrecognized fault trace

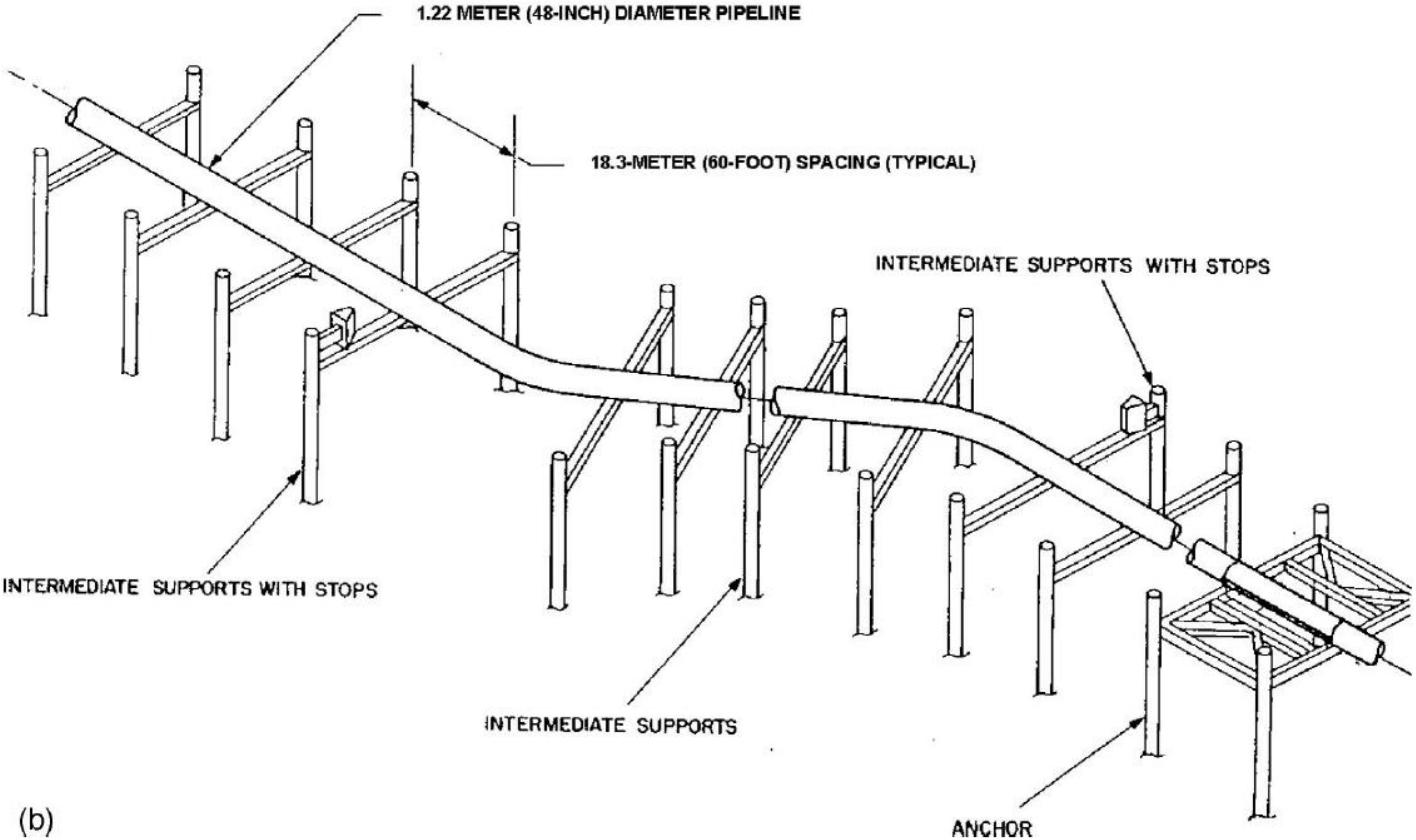
Poor planning in 1954 M 7.1 Fairview Peak earthquake

8 m of compression and uplift in the M 7.7 2001 Chi-Chi earthquake

M 7.9 2002 Denali Earthquake Trans-Alaskan Oil Pipeline



- Pipeline was designed to accommodate shear and compression at the Denali fault
- 6 m lateral slip occurred at the fault crossing
- 12 m slips occurred nearby


1.22 METER (48-INCH) DIAMETER PIPELINE
18.3-METER (60-FOOT) SPACING (TYPICAL)
INTERMEDIATE SUPPORTS WITH STOPS
INTERMEDIATE SUPPORTS WITH STOPS
INTERMEDIATE SUPPORTS
ANCHOR

(b)

Alyeska Trans-Alaskan Oil Pipeline

(a)

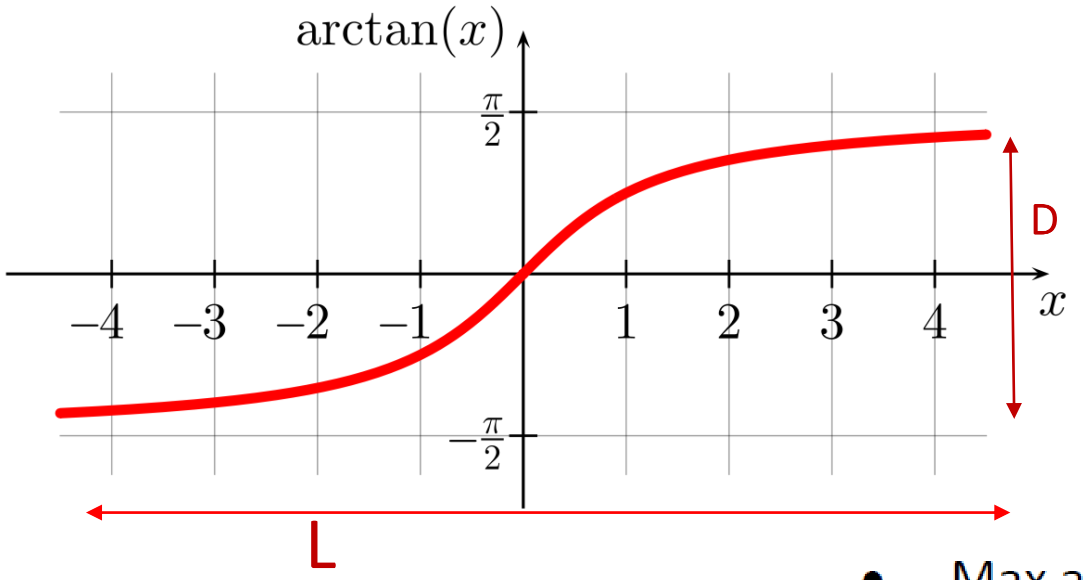
Before earthquake

(b)

After earthquake

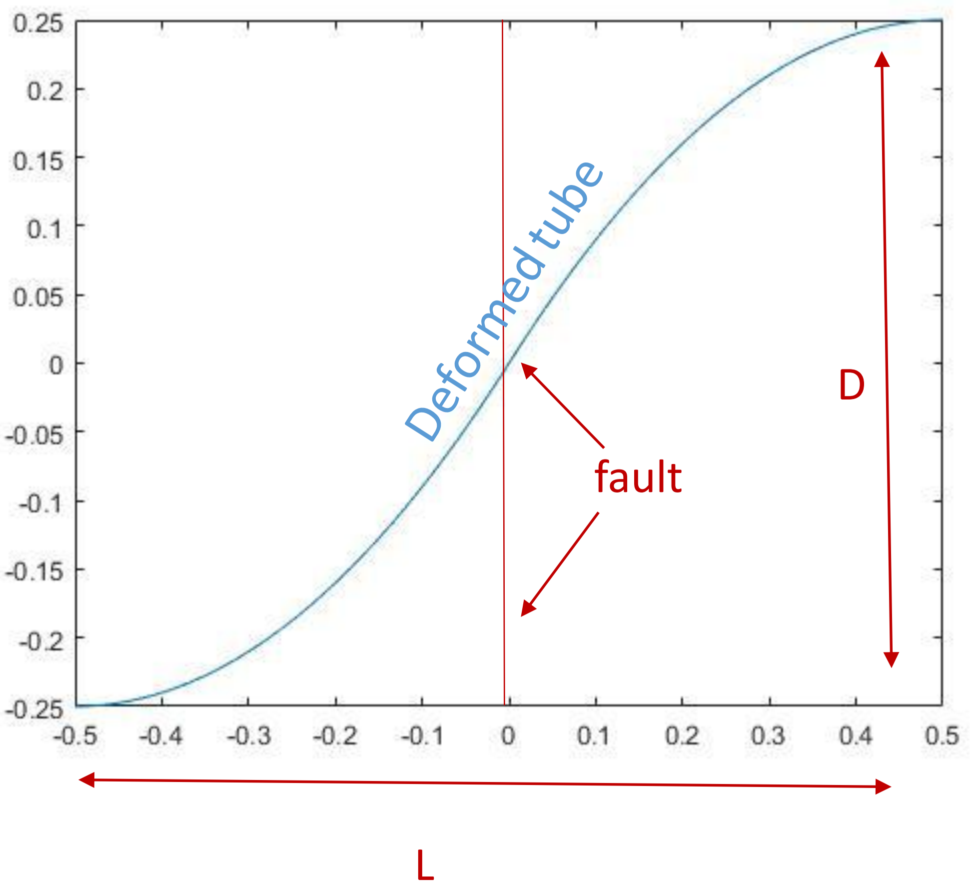
It’s good to be skillfull, but lucky is even better

Arctan is the most "natural" shape



- Max accel at $x = \pm 1$
- Max accel $= \frac{D}{2\pi}\left(\frac{V_{pod}}{L}\right)^2$
- If max accel = 1 g, then $L \approx 44\sqrt{D}$
- 10 m slip requires a total deformation width of about 1.5 km

Constant curvature shape



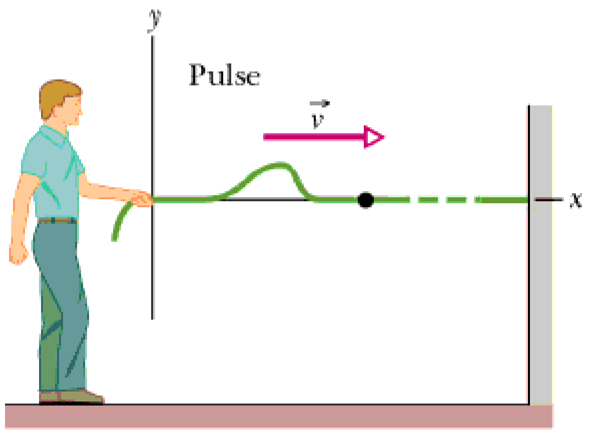
- Parabolic shape
- Constant acceleration in deformed region
- $a_0 = D\left(\frac{2V_p}{L}\right)^2$
- $L = 2V_p\sqrt{D/a_0}$
- If the acceleration was 1g,

  then a 10-m slip would require a 700 m zone

Other considerations for fault crossing

- Fault crossings involve shear and extension/compression
- Many fault scarps occurred on unmapped faults (1/3???)
- Hard to estimate the total offset in future event (it’s most likely a power law)
- North America v Pacific plate rate is 5 m/century

Traveling transverse seismic wave feels different in a high-speed hyperloop pod



$$a_{pod}(t) = \nu^2 a_{ground}(\nu t)$$

$$\nu \equiv 1 - \frac{V_p}{c}$$

c is the apparent wave speed along the tube

- If the pod moves the same velocity as the wave, then the pod stays at a fixed transverse position. You don't feel anything 🙂
- If the pod travels opposite to the wave propagation, then the displacements will be independent of the speed, but they will happen faster. 😬
- Higher accelerations as you travel faster through the wavefield (time is compressed)

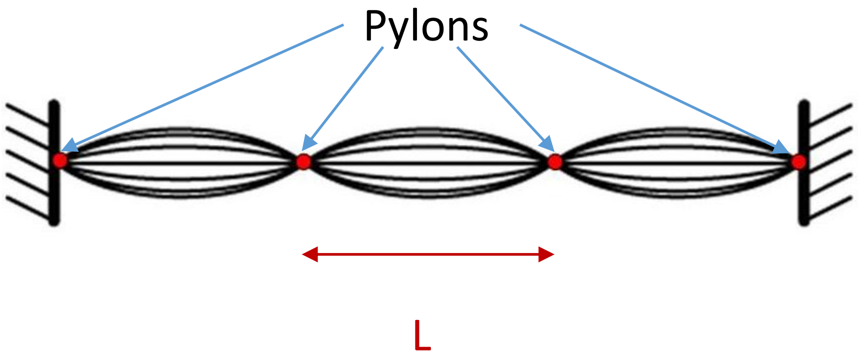
$$a_{pod}(t) = \nu^2 a_{ground}(\nu t)$$

$$\nu \equiv 1 - \frac{V_p}{c}$$

c is the apparent wave speed along the tube

- If c and V_p are in opposite directions, then ν increases.
- If V_p and c are in the same direction, and if $V_p > c$, then time goes backwards. 🤔
- Shear-wave speed in the shallow soils (top 50 m) under UCLA is comparable to 350 m/s
- Apparent wave velocities are much higher; 5 km/s

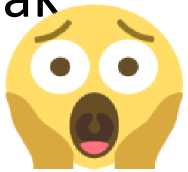
Standing flexural modes of the tube

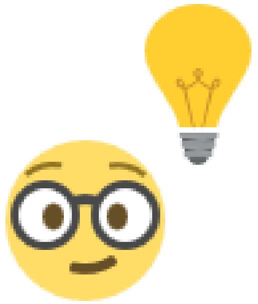


$$\frac{sa_{pod}}{sa_{tube}} \approx 1 + 3 \times 10^{-4} L^2$$

sa is response spectral acceleration

- Assume pinned connection of 3.5 m steel tube at the supporting pylons
- Fundamental flexural period is approximately $T_0 = 10^{-4} L^2$
- 100-m pylon spacing has T_0 = 1 s.
- Large spans can cause large amplifications of pod acceleration at resonant frequencies
- 236-m spacing gives T_0= 5 s and pod amplification of 17 at 5s period
- Using the M 8.1 Kathmandu record to excite a 236-m tube gives peak sway of 3 m and peak pod acceleration of 8.5 g
- This is the most extreme I could think of





Decelerate the pod so it hits the standing wave when the deflection is minimum

- If deceleration a_{brake} is applied when the pod is a distance x_{brake} from the center of the span
- And if the time of the minimum tube deflection is t_{amin} (measured with an accelerometer)
- Then the pod deceleration that causes the pod to hit the span when it's approximately straight is

$$a_{brake} = 2\frac{x_{brake} - V_{pod}\left(t_{a\min} - t_{brake}\right)}{\left(t_{a\min} - t_{brake}\right)^2}$$

- It only takes the pod ½ second to cross the span, so the pod can traverse the span while the tube is approximately straight

Summary

- Above-ground fault crossing can be designed for survivable operation in an earthquake.
- There are curious, but not dangerous, doppler effects due to the high speed of the pod
- The tube should avoid long spans having no supports
- Active control systems may be useful