SOIL-STRUCTURE EFFECTS IN BUILDING RESPONSE

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ABSTRACT

Dynamic interaction between a building-foundation system and the supporting soil can significantly alter the earthquake response of the building depending on the characteristics of the system and the ground motion. The California Strong Motion Instrumentation Program obtained a large number of building response records from the 1 October 1987 Whittier Narrows earthquake. The instrumentation of a 14-story warehouse building included the nearby ground motion. Using this data, this study demonstrates that soil-structure interaction reduces the maximum base shear force in the building.

INTRODUCTION

In the design of building structures to resist earthquake loads or the evaluation of the earthquake response of buildings it is often assumed that the soil supporting the structural system and foundation is rigid. The assumption of a rigid soil does not preclude the use of site dependent ground motion or spectra for input into the building to represent the important effects of the local soil conditions. Assuming a rigid soil, however, neglects the dynamic interaction between a structure-foundation system and the underlying soil. Soil-structure interaction further modifies the input motion and it can significantly alter the earthquake response of structures.

The Whittier Narrows earthquake of 1 October 1987 generated the largest set of strong ground motion records of building response ever obtained from a single event. The California Strong Motion Instrumentation Program (SMIP) collected records from three buildings that included the motion at a ground station close to each building. The recorded ground motion is an estimate of the free-field ground motion, the motion that would occur at the site if the building was not present. Comparison of the free-field ground motion to the basement and building motion can reveal the extent and importance of soil-structure interaction in the dynamic response of the building, foundation, and soil system. Of the three buildings with a free-field instrument, a 14-story reinforced concrete warehouse building was closest to the epicenter and the one which experienced the largest amplitude response. This set of building and ground motion records offers an important opportunity for studying soil-structure interaction effects in building response during a moderate earthquake.

The purpose of this study is to evaluate the records obtained from the warehouse building for soil-structure interaction effects. The results are compared to the National Earthquake Hazards Reduction Program (NEHRP) recommended building code provisions for soil-structure interaction [3].

EVALUATION OF INTERACTION FROM BUILDING RECORDS

The California Strong Motion Instrumentation Program obtained moderate amplitude response records from three buildings with nearby ground motion stations during the 1 October 1987 Whittier Narrows earthquake [4]. Review of the records show that the response of a warehouse building in Los Angeles had significant soil-structure interaction effects. This paper summarizes the investigation of the interaction effects in the building during the earthquake as interpreted from the strong motion records.

Los Angeles Warehouse Building

The Los Angeles warehouse building has been the subject of several investigations using response data collected during earthquakes in 1933, 1952 (Kern County), and 1971 (San Fernando). Figure 1(a) shows the location of the building in relation to the epicenters of previous earthquakes and the 1987 Whittier Narrows earthquake. The availability of both free-field and building records from earthquakes that occurred in the past fifty years, together with the structure's simple design and isolation from other large buildings, make it suited for the study of soil-structure interaction effects.

Figure 1(b) shows location of the triaxial accelerometer in a small shelter structure in the parking lot, 139 ft west of the warehouse building. This instrument records a ground motion that, due to the distance from the building, should not be affected by the dynamic response of the structure and its interaction with the soil. The record approximately represents the free-field motion that would occur at the site if the building was not present. The parking lot instrument, however, is less than one foundation length away from the building in the longitudinal direction, and it is very likely that its motion is affected by interaction between the building-foundation and the soil. For the purpose of this and most previous studies the assumption is made that the parking lot instrument is the free-field ground motion.

The geometry of the building, which was designed and constructed in 1925, is shown in Fig. 2. It is a fourteen-story, 149 ft tall structure with a rectangular cross section that measures 217 ft in the longitudinal EW direction and 51 ft in the transverse NS direction. The lateral force resisting system consists of reinforced concrete frames in both directions. The two exterior longitudinal frames and the westward transverse frame are infilled with 8 in thick panels. The vertical load carrying system consists of 8 in thick concrete slabs supported by columns on capitals. In the three longitudinal bays on the west side of the building, one-way slabs on joists are supported by the transverse frames. A partial basement is located 9 ft below the ground level. The foundation consists of reinforced concrete footings on Raymond concrete piles which vary in depth from 12 ft beneath the footings at the end of the building to about 30 ft near the center.

Data about the soil characteristics at the site of the warehouse building are given in Ref. 2. A soil boring to a depth of 300 ft shows that the building is founded on an approximately 100 ft deep layer of soft, sandy clay. The measured P-wave velocity has a nearly constant value of 2400 ft/s within the layer, except in the superficial shallow stratum of clay loam where it is 1090 ft/s. The sandy clay layer is underlaid by approximately 7000 ft of sedimentary formations, which in turn rests on slate.

The location of the accelerometer sensors installed and maintained in the warehouse building by SMIP are shown in Fig. 3. There are twelve channels in the building and three channels in the parking lot instrument.

To demonstrate that soil-structure interaction was of some importance in this structure during the 1 October 1987 Whittier Narrows earthquake, the maximum acceleration response spectra computed from the corrected and processed records from the parking lot instrument and the basement are shown in Fig. 4. In both directions there is a difference in response in the very short period range. The reduction in basement response compared to the parking lot results from kinematic interaction where the foundation tends to average the effect of the the very short period waves. Of more interest is the difference in response near the fundamental vibration period. In the transverse direction, the fundamental vibration period is 1.9 sec. At this period there is almost no difference in the spectra for the parking lot and basement indicating essentially no change in motion from soil-structure interaction. In the longitudinal direction, the fundamental vibration period is 0.62 sec. The response spectrum for the basement is significantly less than the spectrum ordinate for the parking lot indicating a reduction in basement response because of soil-structure interaction.

Methodology for Evaluation

This study addresses the following question: what is the importance of soil-structure interaction in the engineering design of lateral force resisting systems in buildings? The objective of the study is to determine the lateral forces developed in the warehouse building including soil-structure interaction compared to the lateral forces that would develop if the soil is assumed rigid and interaction effects are neglected. The force quantity of interest is the maximum base shear that occurs during an earthquake.

Although the sensors shown in Fig. 3 give the overall translational and torsional response of the building they are insufficient for determining soil-structure interaction effects. The reasons are:

- There are insufficient acceleration data to compute the inertial forces and hence the lateral forces and shear force at the base of the building.

- It is impossible to determine the response of the building if interaction effects did *not* occur during the earthquake response.

Given these limitations in the available data the following methodology for determining the effects of soil-structure interaction in the warehouse building was adopted:

- Develop a three-dimensional mathematical model of the building superstructure to determine the fixed base vibration properties.

- Use the fixed base vibration properties in a complete model of the building, foundation, and soil in each translational direction.

- Select parameters for the model of the building-foundation-soil system to correlate the model response with the response recorded during the earthquake.

- Compute the response of the building-foundation-soil model including and neglecting the effects of interaction.

A linear, elastic model of the building and soil are assumed in this analysis. This is justified because the moderate earthquake did not result in observed damage of the warehouse. Using this methodology the conclusions on the effects of soil-structure interaction are determined from the building-foundation-soil model which is calibrated to the actual response given by the strong motion records.

Mathematical Model

The fixed base vibration properties of the warehouse building were obtained from the three-dimensional mathematical model shown in Fig. 5(a). The vibration modes and periods were verified using forced vibration data for the building and analysis of response from previous earthquakes. Because the available vibration data includes soil-structure interaction effects an iterative procedure was used to determine the vibration periods of the building on fixed base. In the iterative procedure, a shear wave velocity for the soil of 1190 ft/sec was selected based on the soil data and an estimate of the strain level during the earthquake. The fixed base modes are summarized in Table 1.

The model of the building-foundation-soil system is shown in Fig. 5(b). The model includes motion of the building in each translational direction independently. Torsional effects are not included which is justified because of the near symmetry of the warehouse building. The model of the complete system closely follows the soil-structure interaction analysis procedure presented in Ref. 1. The building is represented by the fixed base vibration modes of the structure which were obtained in the previous step. The foundation-soil system is characterized by frequency-dependent impedance functions that represent the stiffness and energy dissipation characteristics of the foundation and soil. The input motion is the free-field ground motion assuming to occur from vertically propagating shear waves in the soil.

The foundation in the model is assumed to be a rigid circular disk on the surface of the soil [6]. The soil is a homogeneous viscoelastic material extending to infinity below the surface. In addition to the flexibility of the soil, the model represents the material damping that occurs in soil through the viscoelastic properties. The semi-infinite extent of the soil represents the energy radiation that occurs due to waves propagating away from the structure.

The vibration periods in the two translational directions used in the response analysis are given in Table 2. Three vibration modes are used in the transverse direction and two modes in the longitudinal direction. Soil-structure interaction always lengthens the vibration periods because of the flexibility of the soil. The amount of period lengthening depends on the relative stiffness of the building compared to the stiffness of the soil. In the warehouse building the effects of interaction are more pronounced in the longitudinal than in the transverse direction. This difference occurs because the soil is relatively stiff and the flexible transverse frames do not develop large enough base shear and overturning moment to produce significant deformation of the soil. In the longitudinal direction, however, the much stiffer frame and panels develop sufficient base forces to deform the soil.

INTERPRETATION OF RESPONSE RESULTS

After evaluating the vibration properties of the building and soil system, two important parameters of the system must be determined: the damping ratios for the vibration modes in the building and the material damping ratio for the soil. The material damping factor for the soil was assumed to be 0.20 based on an estimate of the strain level and guidelines for sandy clay soils.

The viscous damping ratios for the vibration modes of the building were determined by comparing the frequency response of the system during the 1987 Whittier Narrows earthquake (as given by the processed data from SMIP) and the frequency response of the building-foundation-soil model. The frequency response used in the comparison is the transfer (or transmissibility) function from the free-field and basement to the floors of the building with response records. The transfer function is for total acceleration. Matching the peaks of the transfer functions from the recorded response and the model response gives a viscous damping ratio in the transverse modes of 3.5% and in the longitudinal modes 8.0%.

Figure 6 shows the comparison of the recorded and model transfer function between the free-field and several story levels in the transverse direction. The comparison is excellent. Figure 7 shows the comparison of the recorded and model transfer functions between the basement and several story levels in the longitudinal direction. The comparison is very good indicating that the vibration properties in the transverse direction are well represented.

The comparison of the transfer function between the free-field and several stories in the longitudinal direction is shown in Fig. 8. Here the comparison is not as good. The difficulty in capturing the response of the complete system in the longitudinal direction arises from two sources. The first is that there is some rigid-body torsional motion of the building and foundation that appears as an amplified peak in the transfer function. This cannot be represented in the translational model used in the study. The second major source of the discrepancy is that the parking lot motion is probably not really the free-field ground motion. There appears to be significant coupling between the parking lot and basement instruments because of their proximity compared to the foundation dimensions of the building.

Accepting the comparison, however, as an approximate model of the building-foundation-soil system the maximum base shear of the model is determined by a frequency-domain response analysis using the parking lot records from the 1987 Whittier Narrows earthquake as the free-field ground motion. The maximum base shear obtained from the model is shown in Table 3. In the transverse direction there is little soil-structure interaction, so as expected there is little effect on the base base shear. In the longitudinal direction, the interaction effects are more significant. For this building, soil-structure interaction reduces the maximum base shear by 17%.

CONCLUSIONS

Although there are limitation in the modeling of the system, the response data recorded in the 14 story warehouse building during the 1987 Whittier Narrows earthquake clearly shows that soil-structure interaction reduced the base shear by a significant amount in the longitudinal direction. The concept of base shear reduction is codified in the NEHRP recommendations for soil-structure interaction [3] and in accordance with soil-structure interaction principles [6]. Using the proposed procedure, a 3% reduction in base shear would be allowed in the transverse direction and a 9% reduction in the longitudinal direction.

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TABLE 1. Fixed Base Vibration Modes and Periods
of 14-Story Warehouse Building

No.	Mode	Period (sec)
1	translational-transverse	1.80
2	torsional	0.88
3	translational-longitudinal	0.58
4	translation-transverse	0.55
8	translational-longitudinal	0.18

TABLE 2. Vibration Periods (in sec) of
14-Story Warehouse Building Neglecting
and Including Soil-Structure Interaction

	Transverse Direction		Longitudinal Direction	
No.	Neglecting SSI	Including SSI	Neglecting SSI	Including SSI
1	1.80	1.90	0.58	0.62
2	0.55	0.56	0.18	0.19
3	0.29	0.30	—	—

TABLE 3. Maximum Base Shear (in kip) of
14-Story Warehouse Building Neglecting
and Including Soil-Structure Interaction

Direction	Neglecting SSI	Including SSI	Change
Transverse	927	924	-0.3%
Longitudinal	4750	3960	-17%

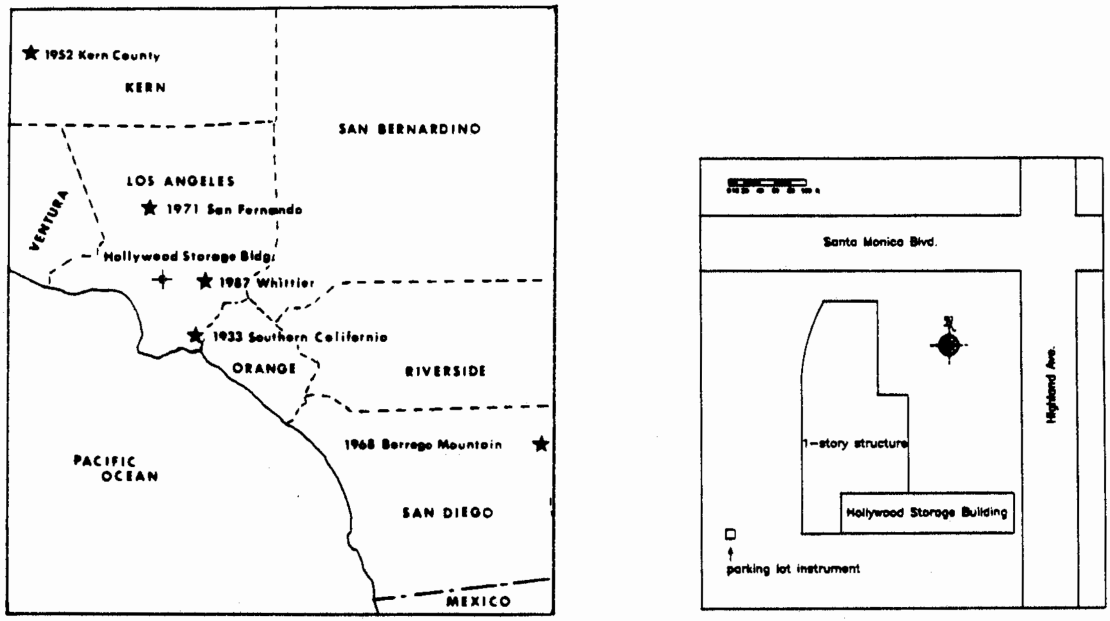


FIGURE 1. Location of 14-Story Warehouse Building. (a) Epicenters of Previous Earthquakes, (b) Location of Sensors in Parking Lot.

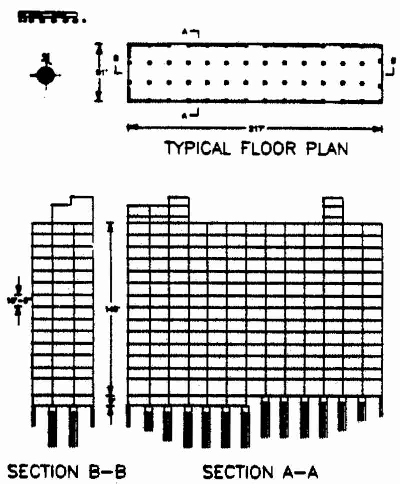


FIGURE 2. Structural System of 14-Story Warehouse Building.

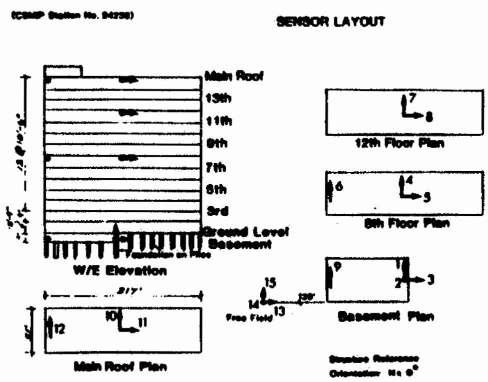
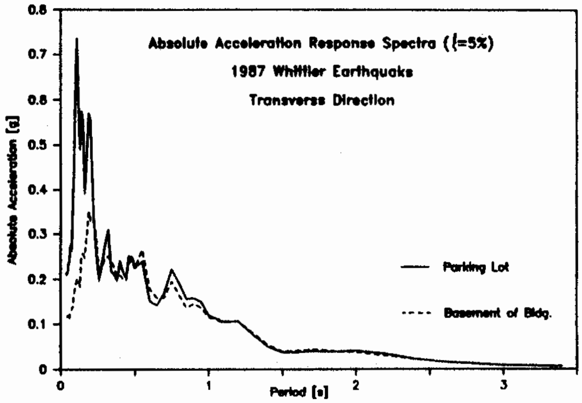


FIGURE 3. Locations of SMIP Accelerometer Sensors [4].



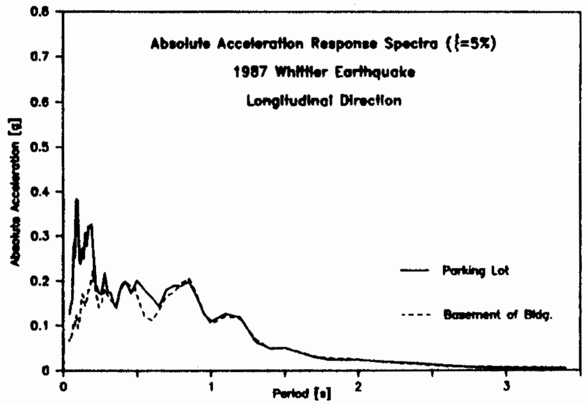
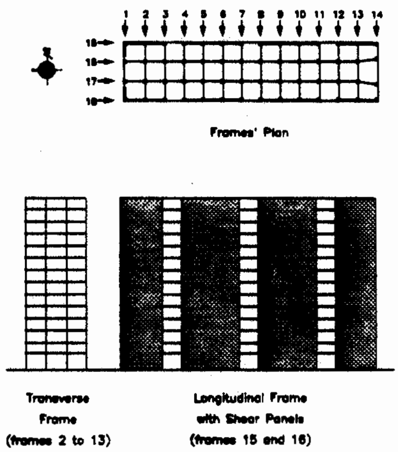


FIGURE 4. Absolute Acceleration Response Spectra for Parking Lot and Basement Records From the 1987 Whittier Narrows Earthquake.



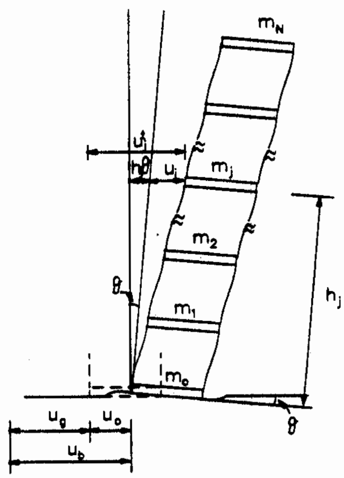


FIGURE 5. Mathematical Model of 14-Story Warehouse Building.
(a) Building Superstructure, (b) Building-Foundation-Soil System.

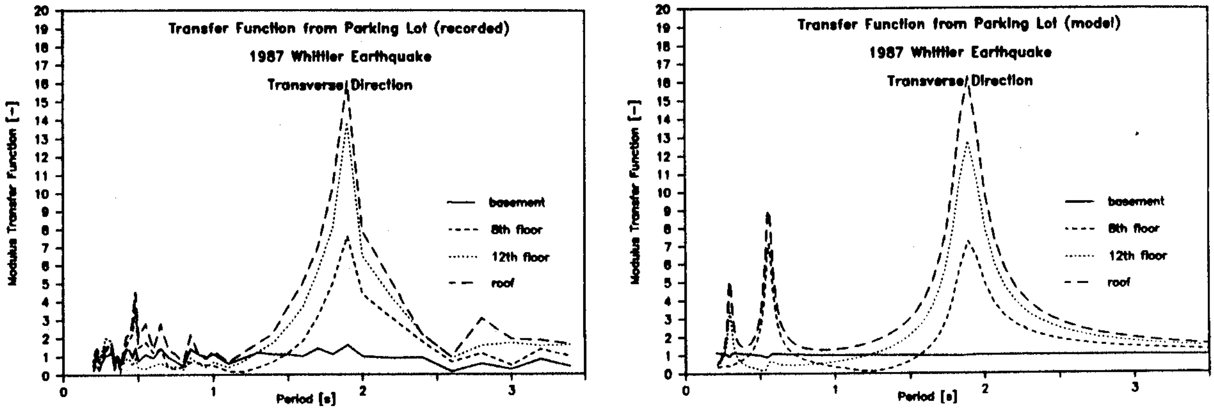


FIGURE 6. Transfer Function Between Free-Field and Story Levels in the Transverse Direction.

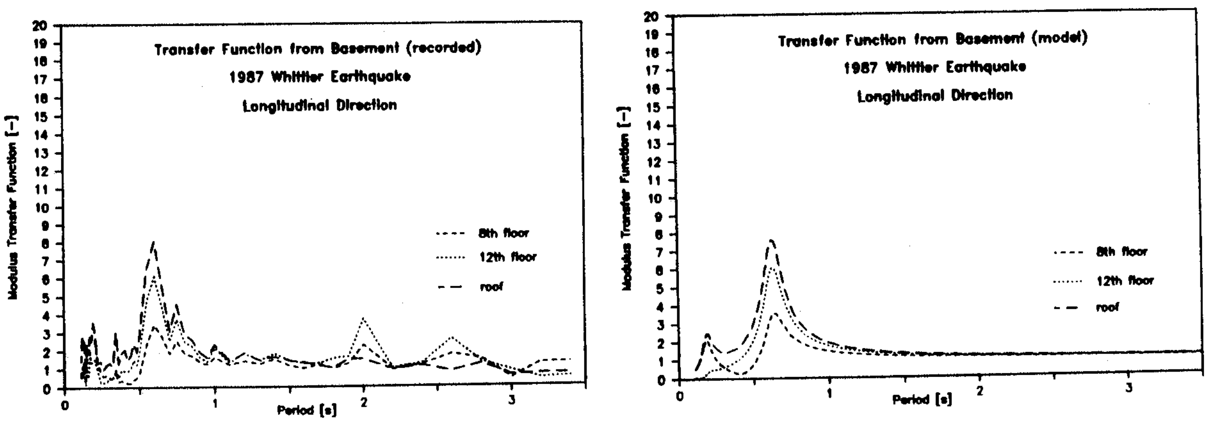


FIGURE 7. Transfer Function Between Basement and Story Levels in the Longitudinal Direction.

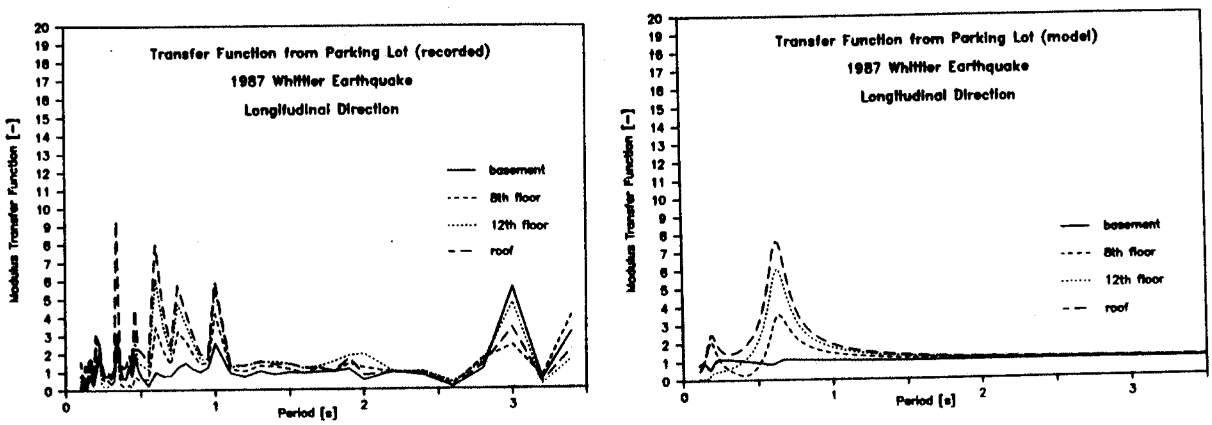


FIGURE 8. Transfer Function Between Free-Field and Story Levels in the Longitudinal Direction.