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Lecture Series:

Structural Dynamics

Lecture 11:

Earthquake Excitation:

Part A: Basics

Overview

- Some remarks on earthquakes
- Earthquake damages: slide show
- Time-domain response to earthquake excitation via inertial forces
- Outlook:
  - Response spectrum method
  - Time-domain response via imposed displacements

Cause of Earthquakes

tectonic activity: relative movement of tectonic plates

- stresses between the plates
- local failure: sudden release if stresses are too large
- shock wave propagation from the epicenter
  - longitudinal waves
  - shear waves
  - surface waves

special area of physics: seismology

Effects of Earthquakes

large-scale geophysical process: huge amount of energy is released!

large-scale damage:

- loss of life
- buildings destroyed
- infrastructure destroyed
  - secondary damage

special discipline within civil engineering:

EARTHQUAKE ENGINEERING

Basel, October 10, 1356

“Das Erdbeben in Basel”, painting by Karl Jauslin (1842–1904); public domain; source: Wikimedia Commons

Basel, October 10, 1356

Das Basler Erdbeben bezeichnet eine Serie von gewaltigen Erdstössen, die Basel ab dem Nachmittag des Lukastages (18. Oktober) des Jahres 1356 in Trümmer legten. Es begann etwa um vier Uhr nachmittags mit einem ersten Stoss. Viele Häuser und der Chor des Basler Münsters stürzten ein. Von Panik ergriffen flüchteten die Bewohner der Stadt aufs offene Feld. Abends von zehn Uhr bis Mitternacht folgten weitere, schwerere Stösse. Schäden wurden bis in 50 Kilometer Entfernung festgestellt. Die Stadt geriet in Brand; was das Beben nicht in Trümmer gelegt hatte, wurde ein Raub der Flammen. Das Dach des Münsters stürzte ins Kirchenschiff und zerstörte die Altäre, die Orgel und die Bilder. Acht Tage lang habe das Feuer gewütet, bis es schliesslich keine Nahrung mehr fand. Fast alle Kirchen der Stadt und vierzig Burgen im Umkreis wurden beschädigt.

Der Mittelpunkt des Erdbebens lag unter dem Dorf Reinach, einige Kilometer südlich der Stadt Basel. Dort verläuft ein tiefer Riss in der Erdkruste und reicht von Aesch aus in zwei Armen weit nach Norden. Entlang dieses Risses sank vor vielen Millionen Jahren die Birs- und Rheinebene in die Tiefe.

Die Anzahl der Todesopfer des Bebens war begrenzt, da viele nach dem Vorbeben am Nachmittag aus der Stadt geflüchtet waren. Schätzungen gehen von 300 bis 1000 Todesopfern aus. Der Wiederaufbau konnte so sehr bald beginnen und schon im Frühsommer 1357 war Basel zu einem normalen Stadtalltag zurückgekehrt. Bis etwa 1370 wurden die durch das Erdbeben zerstörten Gebäude wiederhergestellt.

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Die Schweizer Erdbebenkatastrophengruppe der ETH Zürich stellt fest: „The earthquake that occurred on October 18, 1356 in the region of Basel is the strongest historically documented earthquake in central Europe.“ (Das Erdbeben, das sich am 18. Oktober 1356 in der Gegend von Basel ereignete, ist das stärkste, das in historischer Zeit in Zentraleuropa dokumentiert wurde.)

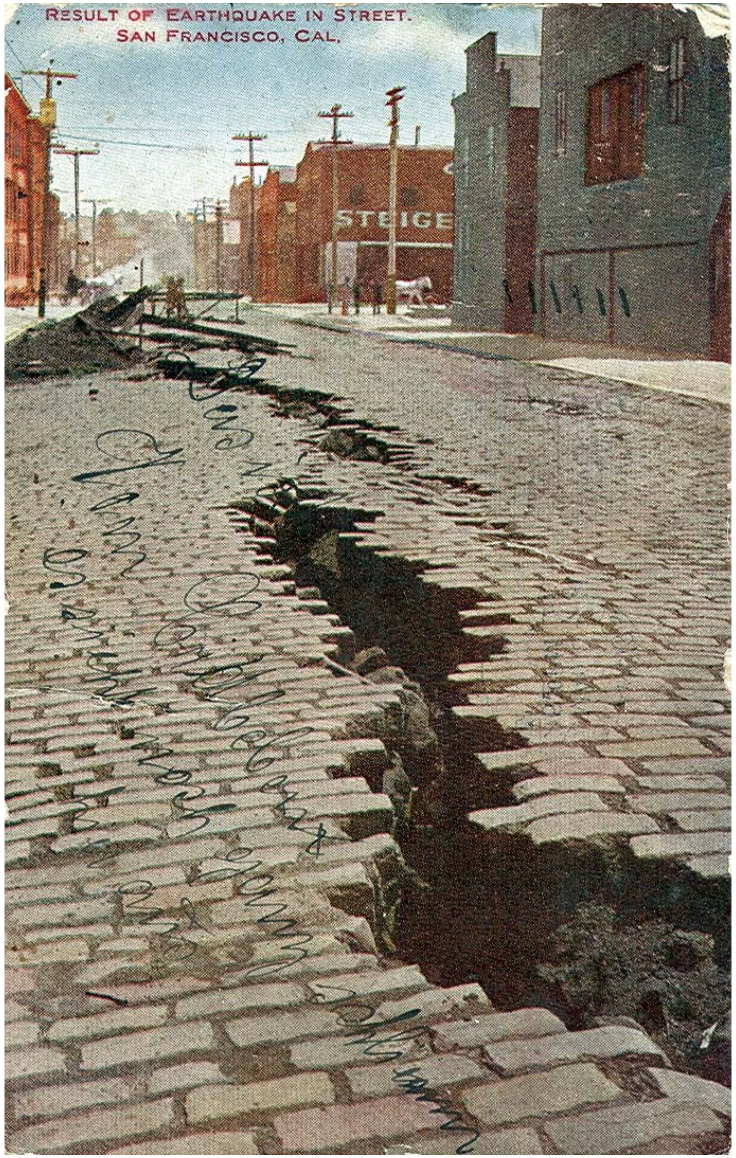
Source: WIKIPEDIA

Terremoto del Monte Vulture, July 22, 1930

Il terremoto del Monte Vulture di magnitudo 6,7° Richter si verificò il 23 luglio 1930 e colpì soprattutto la Basilicata, la Campania e la Puglia; ebbe i suoi massimi effetti nella zona montuosa fra le provincie di Potenza, Matera, Benevento, Avellino e Foggia. Il terremoto causò la morte di 1404 persone prevalentemente nelle province di Avellino e Potenza, interessando oltre 50 comuni di 7 province. Il sisma fu aggravato dalla scarsa qualità dei materiali usati per le costruzioni e dalla natura argillosa dei terreni.

Source: WIKIPEDIA

San Francisco 1906



The San Francisco earthquake of 1906 was a major earthquake that struck San Francisco, CA and the coast of Northern California at 5:12 A.M. on Wednesday, April 18, 1906.[2] The most widely accepted estimate for the magnitude of the earthquake is a moment magnitude (Mw) of 7.8; however, other values have been proposed, from 7.7 to as high as 8.25.[3] The main shock epicenter occurred offshore about 2 miles (3 km) from the city, near Mussel Rock. It ruptured along the San Andreas Fault both northward and southward for a total of 296 miles (477 km).[4] Shaking was felt from Oregon to Los Angeles, and inland as far as central Nevada. The earthquake and resulting fire is remembered as one of the worst natural disasters in the history of the United States. The death toll from the earthquake and resulting fire, estimated to be above 3,000,[5] is the greatest loss of life from a natural disaster in California's history. The economic impact has been compared with the more recent Hurricane Katrina.[6]

Source: WIKIPEDIA

Postkarte, datiert 30.5.1908. Titel: "Folge des Erdbebens auf der Straße. San Francisco, Cal." In Deutsch über die Vorderseite der Karte gekritzelt: "Das ist vom Erdbeben. Es sieht noch immer ganz schlimm hier aus."

Source: private collection of Wolfgang Sauber (Xenophon)

Author: Anonymous

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Abruzzo, April 6, 2009

The 2009 L'Aquila earthquake was an earthquake that occurred in the region of Abruzzo, in central Italy. The main shock occurred at 3:32 local time (1:32 UTC) on 6 April 2009, and was rated 5.8 on the Richter scale and 6.3 on the moment magnitude scale;[5] its epicentre was near L'Aquila, the capital of Abruzzo, which together with surrounding villages suffered most damage. There have been several thousand foreshocks and aftershocks since December 2008, more than thirty of which had a Richter magnitude greater than 3.5.[5]

The earthquake was felt throughout central Italy; 307 people are known to have died,[3] making this the deadliest earthquake to hit Italy since the 1980 Irpinia earthquake.

…

Poor building standards or construction materials seem to have further contributed to the large number of victims. According to firefighters and other rescuers, some concrete elements of the fallen buildings "seemed to have been made poorly, possibly with sand".[33] An official at Italy's Civil Protection agency, Franco Barberi, said that "in California, an earthquake like this one would not have killed a single person".[34] According to Italian media, L'Aquila's chief prosecutor has opened a probe into possible criminal blame for the collapses.

Source: WIKIPEDIA

Abruzzo, April 6, 2009

photograph by Francesco Eusani, used by kind permission

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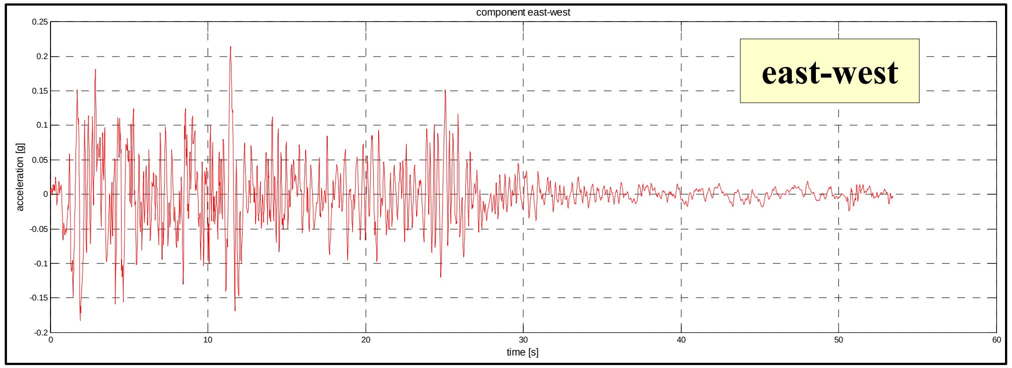
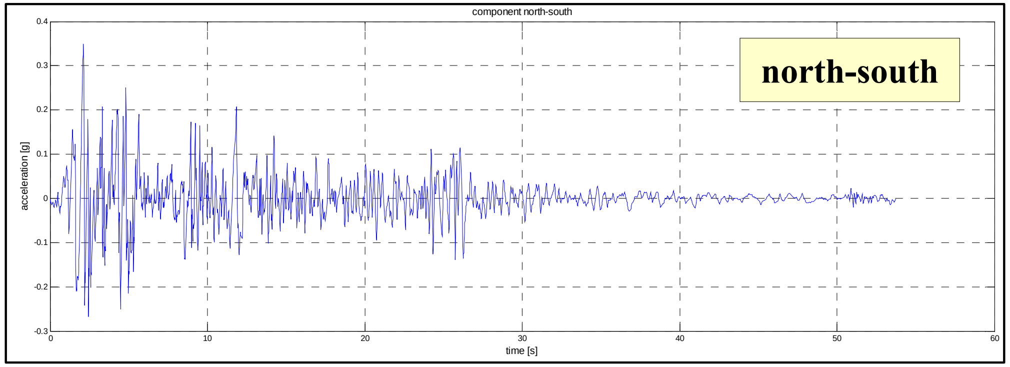
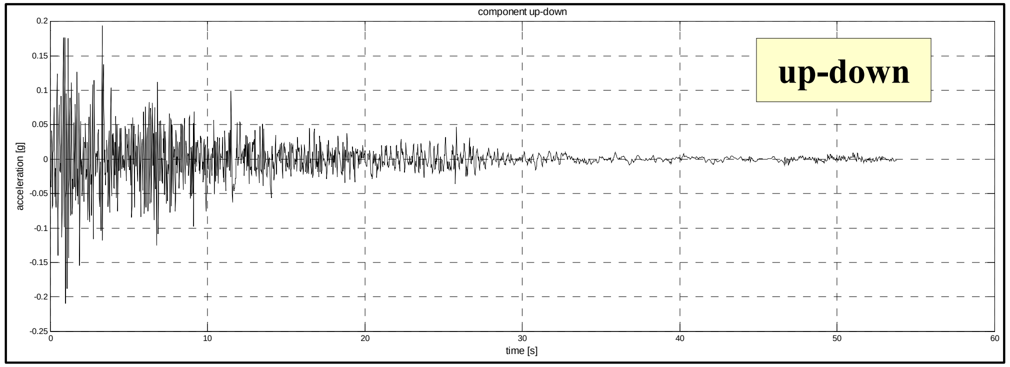
Earthquake Excitation: Ground Acceleration







Seismic stations measure the ground acceleration a_g. A time history of a_g is called an *accelerogram*. The acceleration is a vector with three components; usually we split the ground acceleration into two horizontal components defined in *east-west* and *north-south* direction and one vertical component *up-down*.

Shown on the left are the three components of the El Centro earthquake.

USGS (U.S. Geological Survey) description of the El Centro (Imperial Valley) earthquake:

"Nine people were killed by the May 1940 Imperial Valley earthquake. At Imperial, 80 percent of the buildings were damaged to some degree. In the business district of Brawley, all structures were damaged, and about 50 percent had to be condemned. The shock caused 40 miles of surface faulting on the Imperial Fault, part of the San Andreas system in southern California. It was the first strong test of public schools designed to be earthquake-resistive after the 1933 Long Beach quake. Fifteen such public schools in the area had no apparent damage. Total damage has been estimated at about $6 million. The magnitude was 7.1."

Earthquake Components

vertical structures:
only horizontal components important

source: wikimedia commons, used by GFDL licence, © Taxiarchos228

horizontal structures:
also vertical component important

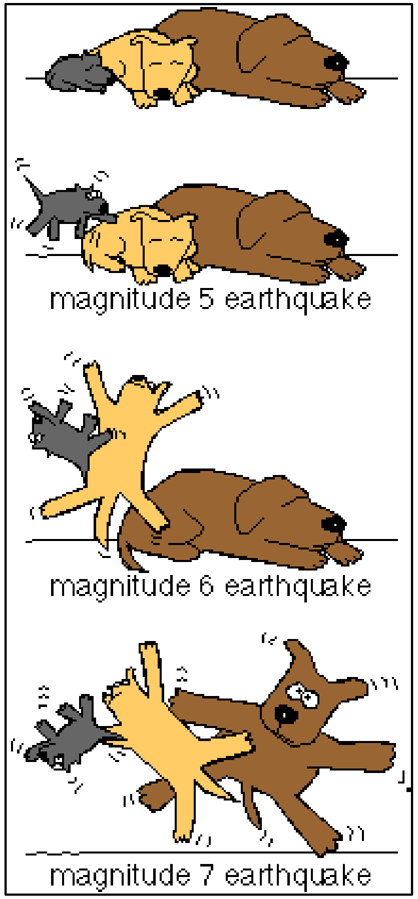
Picture taken by Adrian Pingstone in October 2003 and placed in the public domain.

Damage Potential

Ground acceleration:
- **instationary (stochastic) process.**
- **broad-band excitation: a large frequency band is activated.**

Damage potential:
- **magnitude**
    - **PGA: peak ground acceleration**
- **total energy**
- **duration**

damage potential depends on the location



Earthquake Engineering

(A) Development of ***methods*** (analytical and numerical ones) to calculate the response of buildings under seismic loading:

   (i) displacements and stresses,

   (ii) damage state.

(B) Development of ***design concepts*** to make buildings more "resistent" or "safe" with respect to seismic effects.

In this lecture series we will concentrate mainly on aspect A. The question of how to design structures and individual members with regard to seismic excitation belongs to the field of structural engineering proper, e.g. the lectures on concrete structures and steel structures. We will address these questions only very briefly in the Part B of Lecture 11 when we discuss the inelastic design response spectra.

Treatment of Ground Acceleration

From the viewpoint of an outside observer: the total displacement V_{tot} of a point belonging to the structure can be split into the displacement relative to the ground V_{rel} and the displacement V_{ground} of the ground itself:

$$\mathbf{V}_{tot} = \mathbf{V}_{ground} + \mathbf{V}_{rel}$$

mass forces:
related to the *total* accelerations

$$\mathbf{F}_{m} = \mathbf{M}\,\ddot{\mathbf{V}}_{tot}$$

damping forces:
related to the *relative* velocities

$$\mathbf{F}_{c} = \mathbf{C}\,\dot{\mathbf{V}}_{rel}$$

stiffness forces:
related to the *relative* displacements

$$\mathbf{F}_{k} = \mathbf{K}\,\mathbf{V}_{rel}$$

Seismic Loads as Inertial Forces

The equation of motion for an earthquake excitation contains both V_{rel} and V_{tot}. In principle it would always have been necessary to differentiate between relative and total. Up until now, however, we have only dealt with excitations in the form of external forces where the supports were fixed and the relative displacements were therefore equal to the total displacements.

$$\mathbf{M}\,\ddot{\mathbf{V}}_{\mathrm{tot}} + \mathbf{C}\,\dot{\mathbf{V}}_{\mathrm{rel}} + \mathbf{K}\,\mathbf{V}_{\mathrm{rel}} = \mathbf{0}$$

$$\ddot{\mathbf{V}}_{\mathrm{tot}} = \ddot{\mathbf{V}}_{\mathrm{ground}} + \ddot{\mathbf{V}}_{\mathrm{rel}}$$

$$\mathbf{M}\,\ddot{\mathbf{V}}_{\mathrm{rel}} + \mathbf{C}\,\dot{\mathbf{V}}_{\mathrm{rel}} + \mathbf{K}\,\mathbf{V}_{\mathrm{rel}} = -\mathbf{M}\,\ddot{\mathbf{V}}_{\mathrm{ground}} = \mathbf{P}_{\mathrm{quake}}$$

The ground acceleration leads to inertial forces which act as external loading for the calculation of the relative displacements which are responsible for stresses and possible damage.

Computation of the Seismic Load

Relativity Principle:

The acceleration of a *mobile ground* with respect to a *fixed structure* is equivalent to the acceleration of a *mobile structure* with respect to a *fixed ground*.

Since we want to calculate the relative displacements, we fix the supports and treat the structure as being accelerated with respect to the fixed supports. All nodes then are subjected to the same acceleration.

$$\ddot{\mathbf{V}}_{\text{ground}}(t) = \mathbf{X}\, a_g(t) \quad \Rightarrow \quad \mathbf{P}_{\text{quake}} = -\mathbf{M}\,\mathbf{X}\, a_g = \mathbf{P}_{m,\text{unit}}\, a_g$$

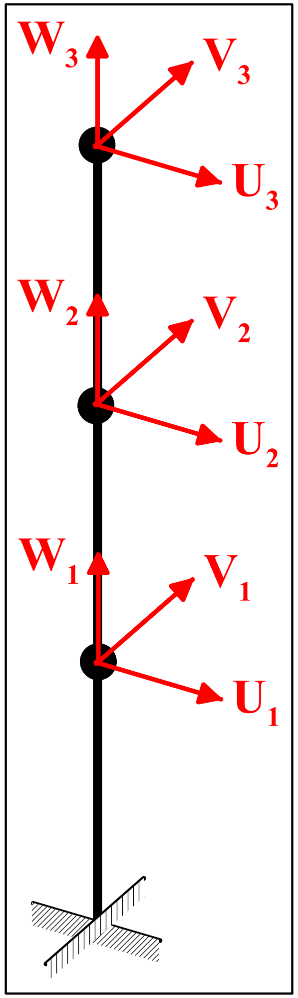
The function $a_g(t)$ contains the *scalar time history* of the ground acceleration. The vector X contains information regarding the *direction of the quake*, i.e. which degrees of freedom experience inertial forces. For a quake parallel to the global reference frame we have a simple on/off situation: an element of X is set to

- **1 if the degree of freedom coincides with the direction of the quake,**
- **0 otherwise.**

The elements corresponding to rotations are always set to zero.

Example: Quake in Y-Direction

vertical beam with 9 dofs (rotations ignored for simplicity's sake)



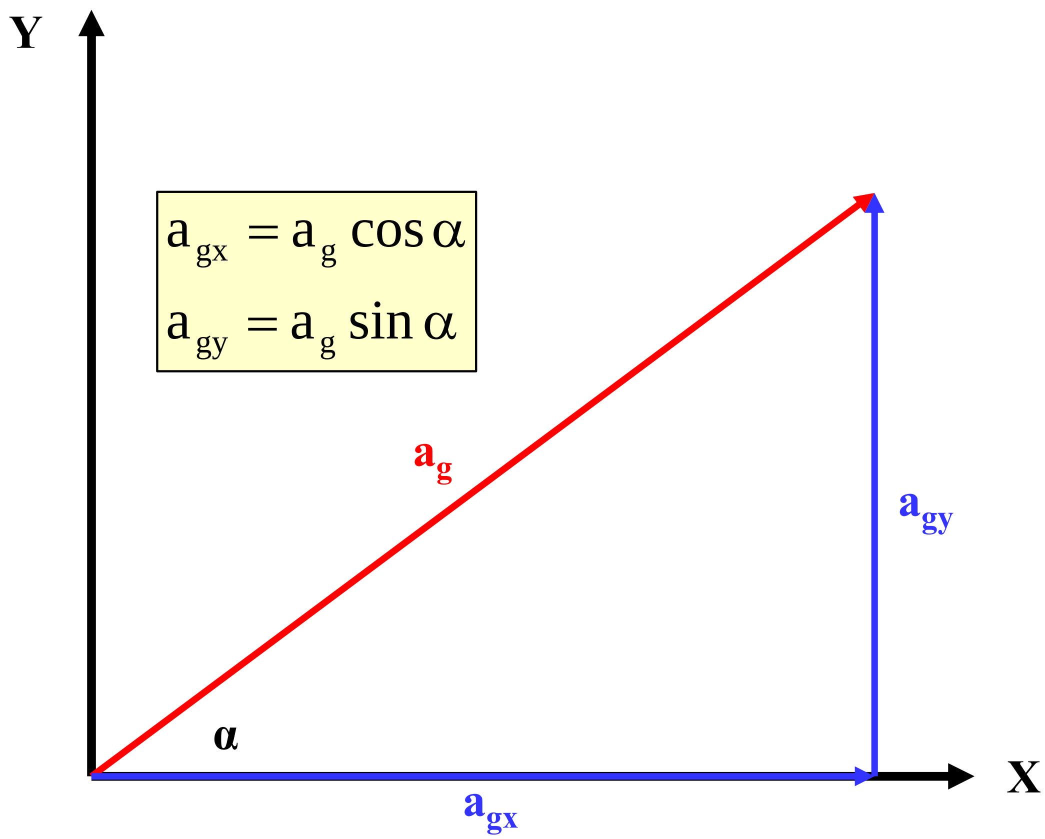
quake comes from global y-direction:

$$\ddot{\mathbf{V}}_{\text{ground}}(t) = \begin{bmatrix} \ddot{U}_1 \\ \ddot{V}_1 \\ \ddot{W}_1 \\ \ddot{U}_2 \\ \ddot{V}_2 \\ \ddot{W}_2 \\ \ddot{U}_3 \\ \ddot{V}_3 \\ \ddot{W}_3 \end{bmatrix} = a_g(t) \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

Example: Quake in the XY-Plane

If the quake comes from an arbitrary direction, we can split it into two components with regard to the global X- and Y- Axes:

$$a_{gx} = a_g \cos\alpha$$
$$a_{gy} = a_g \sin\alpha$$



quake comes from arbitray direction:

$$\ddot{V}_{ground}(t) = \begin{bmatrix} \ddot{U}_1 \\ \ddot{V}_1 \\ \ddot{W}_1 \\ \ddot{U}_2 \\ \ddot{V}_2 \\ \ddot{W}_2 \\ \ddot{U}_3 \\ \ddot{V}_3 \\ \ddot{W}_3 \end{bmatrix} = a_g(t) \begin{bmatrix} \cos\alpha \\ \sin\alpha \\ 0 \\ \cos\alpha \\ \sin\alpha \\ 0 \\ \cos\alpha \\ \sin\alpha \\ 0 \end{bmatrix}$$

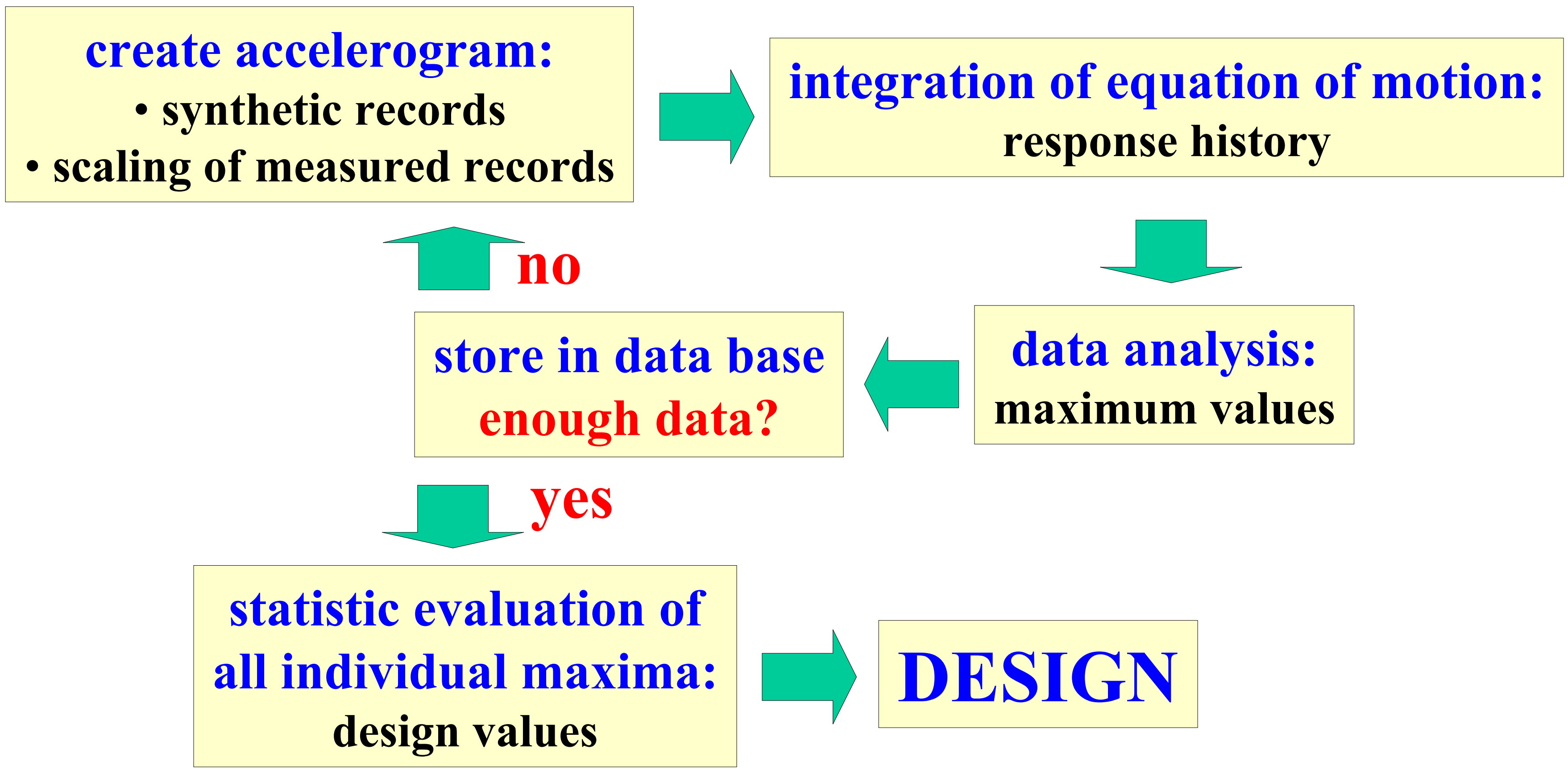
History of the Ground Acceleration

Form the algorithmic viewpoint we have a standard problem once we have computed the inertial load vector. The problem can be solved by any suitable method, usually we employ a direct time integration algorithm.

Not standard is the question of how to find the ***time history of the ground acceleration***. The ground acceleration is a ***stochastic process***: there are no fixed formulas with which to compute a time history. Such formulas cannot exist since we have a ***random non-repeatable process***. If we measure acceleration histories at one specific point over an extended period of time, we would never measure the same history twice. At the maximum we could extract some common characteristics from our measurements which reflect the local geological situation, but it would be impossible to forecast a history for the next quake.

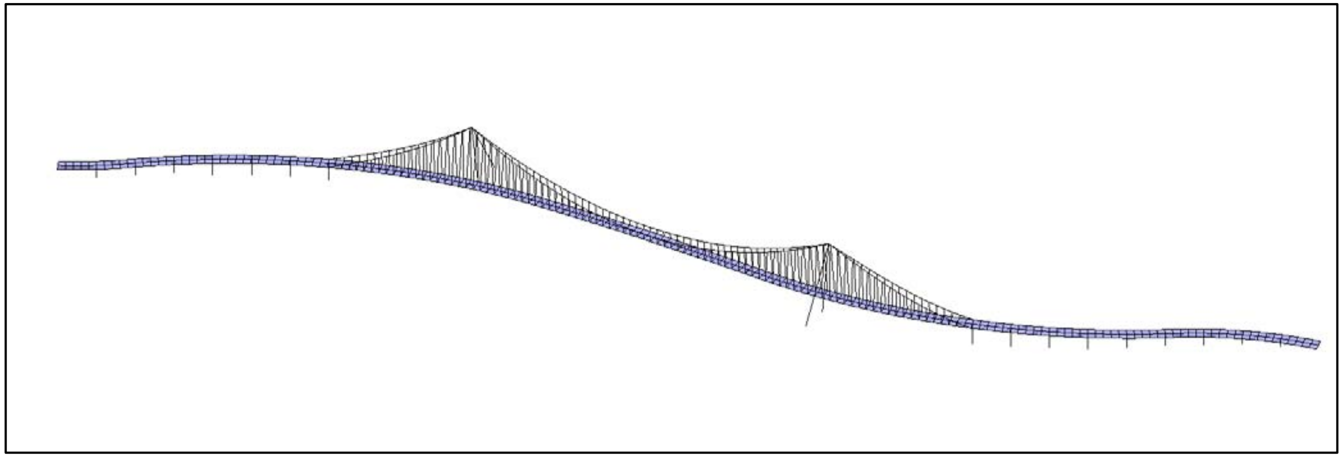
This is a general problem for all natural processes. We encounter the same difficulties when trying to model stochastic wind forces for a bridge design or stochastic wave forces for offshore structures. There have been developed special numerical algorithms to generate synthetic records of such stochastic processes – we will discuss these in Part C of this lecture. These records have one common drawback: they represent only ***one random sample*** of the entire process with only ***limited information content***. To come to reliable design values we have to generate a whole batch of excitation histories and run a corresponding number of dynamic analyses from which we then compute design values by techniques of extreme value statistics.

Time Domain Approach – Flow Chart



Outlook I: Correlation of the Ground Movement

The relativity principle tacitly assumes that all supports are moved in exactly the same way by one single acceleration history. Then we can apply that history to all nodes for our inertial forces. That, however, is only true if the geometrical extension of the base of the structure is so small that we have the same soil characteristics and no noticeable effects a wave propagation within the base. For buildings such as high rises this is true.



It is not true, on the other hand, for bridges whose span exceeds a certain length. Then we observe a certain de-correlation of the acceleration histories at the different supports. This effect must, according the EUROCODE 8, be taken into account. Then we need more advanced analysis concepts than the simple uniform inertial acceleration. More on this in Part C of Lecture 11: “Time Domain Analysis via Correlated Histories of Ground Displacements”.

Outlook II: Response Spectrum Method

All time domain simulations of seismically excited structures have the drawback that one analysis alone is not sufficient to capture the entire stochastic process: we need a *batch of simulations* to obtain *statistically reliable design values*. Such a high numerical effort might be justified for expensive structures such as long-span bridges, where the costs of the simulations still remain small compared to the total cost. For everyday problems, however, such complex analyses would be uneconomical. Also we must realize that the average civil engineer has neither the knowledge regarding structural dynamics nor the special software to perform such simulations.

Here we need a simplified method which is at once fast and relatively easy to use. This method is the so-called *response spectrum method*. We will discuss it in Part B of Lecture 11.