Deliverable

RISE-D2.7: Results of excitation sources and recommendations

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Lead	BOUN - KOERI
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1. Introduction

With the rapid developments in instrumentation and communication technologies, field-testing is now increasingly replacing analytical modelling and laboratory testing to assess the dynamic response of structures. Today, a large number of structures are being monitored, either continuously with permanent monitoring systems, or temporarily with portable monitoring systems. Since natural excitation sources like earthquakes are not frequent, there is a need for man-made excitation sources to test such structures.

As part of BOUN-KOERI's responsibility in WP2.3 of RISE, we have designed and have manufactured two such equipment to test structures: an Impact Hammer (IH) and an Eccentric Mass Shaker (EMS). Each equipment is small and portable enough to be disassembled and moved to any floor of a multi-story building via elevators.

This report presents the technical specifications and user manuals of IH and EMS, and their utilization in testing structures. We present examples of data collected and information that can be extracted from the data.

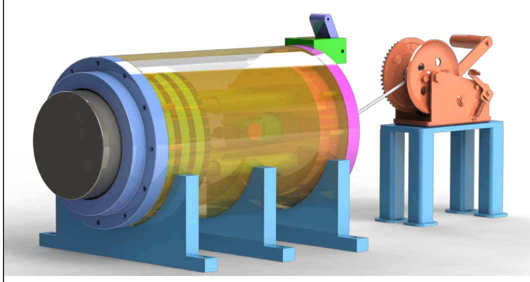
2. IH - Impact Hammer

The objective in developing an impact hammer is to give an impulsive force to a multi-story building and measure the propagation (i.e., the arrival times) of the impulse along the height of the building. The impulsive forces can be given from any floor by moving the Impact Hammer. These data are used to identify each story as if it were a one-story structure and to determine wave propagation characteristics of seismic waves in multi-story buildings. The response is measured by acceleration sensors. The measurements are used to identify the natural frequency and damping ratio of each story, as well as the wave travel times in the building, wave reflection and transmission coefficients at floor levels, and story damping. It is shown that such information provides a better insight into the dynamic characteristics of the building than the modal properties.

The impact hammer is designed to be small and light enough such that it can be disassembled and moved to any floor of the building, including the roof, via elevators and does not require electrical power.

The design drawings of the Impact Hammer are given below, in Fig. 1. It involves four springs, a lever to set the springs, and a release button. It can transfer the impulsive force to the building via floor slab by attaching the Impact Hammer to the floor, or via a wall or column by placing it against them, as shown in Fig. 2.

More detail on its design and technical specifications of IH are given in Appendix I.



Momentum Capacity (kgxm/s)	100
Impact mass (kg)	80
Maximum contraction (mm)	54
Impact area (mm²)	31400
Maximum Velocity (mm/s)	1250 mm/s
Number of springs	4
Maximum force need for setting the springs (N)	~2000 N = 200 kg
Maximum height (mm)	430
Maximum width (mm)	466
Maximum length (mm)	~1000

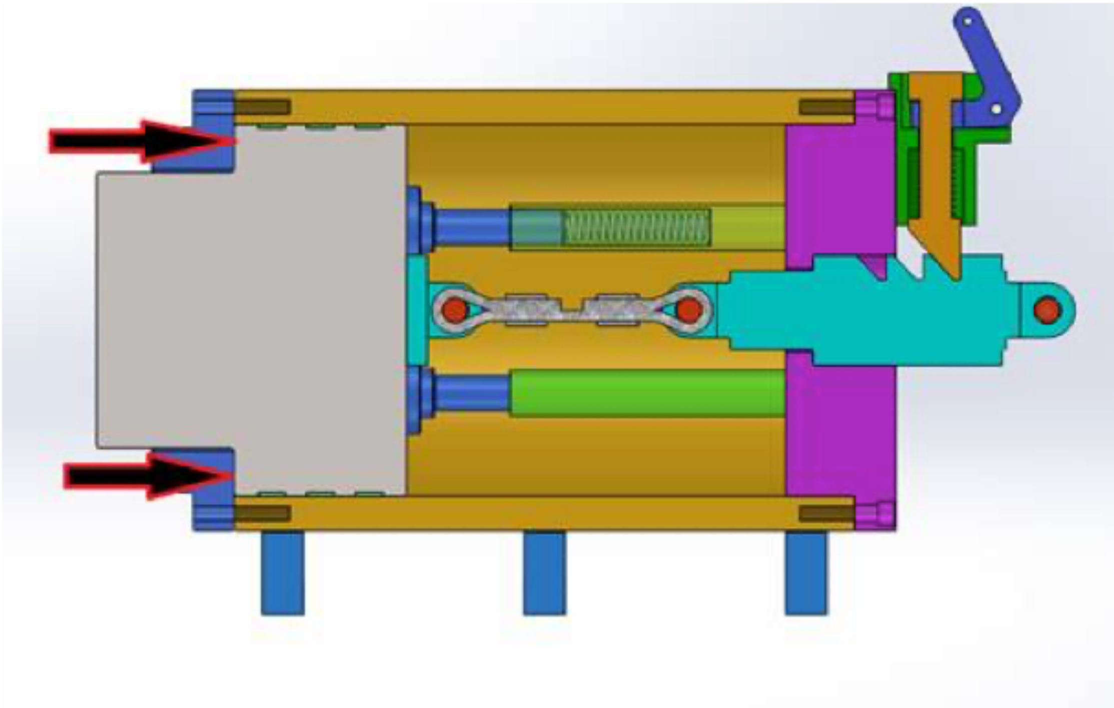


Figure 1. Specifications and cross-section of the Impact Hammer.

Figure 2. Use of Impact Hammer: (a) Attached to the floor, (b) Placed against a column

3. Placement of IH-Impact Hammer in a building

When selecting the location for the Impact Hammer on a floor, it is important that the impulsive force given by the IH should mobilize the entire structure, not the local element that the force is applied to. In a typical multi-story apartment building, an appropriate place would be against one of the shear walls surrounding the elevator shaft, generally placed near the centre of the cross-section. An alternative location would be a beam-column connection near the centre and the IH is typically placed to impact the column bottom near the floor slab. Alternatively, the IH can be attached to the floor slab by the base plate and six connecting bolts, as shown in Fig. 2a, above. The connecting bolts of IH and the in-plane stiffness of the floor slab should be strong enough such that the impact force is transmitted to the structural system via the floor slab without any slippage or loss of force at the installation. Again, the location of IH should be close to the centre, preferable near a major a vertical component of the building, such as a shear wall or a column.

The direction of IH force should be in the direction of one of the two major structural axes of the building. Generally, two applications of IH force are required, one for each structural axis. If the building is not symmetric, such that significant torsional motions are expected, additional tests should be performed by placing the IH near the edges of the cross-section.

(a) (b)

4. An example of IH data

The Impact Hammer have been tested in two instrumented multi-story buildings, the Polat Tower and the Sapphire Building in Istanbul. The properties of the buildings and the details of their instrumentation are given in Appendix III.

As an example, Fig. 3 shows the IH data from the 34-story Polat Building when impacted at the 34^{th} floor. In the figure, acceleration time histories recorded at the 34^{th}, 24^{th}, 17^{th}, and 15^{th} are plotted. It is clear that the impulse can be detected by the sensors clearly all the way down at the 17^{th} floor, which is 17 floors below the impacted floor (i.e., the top floor).

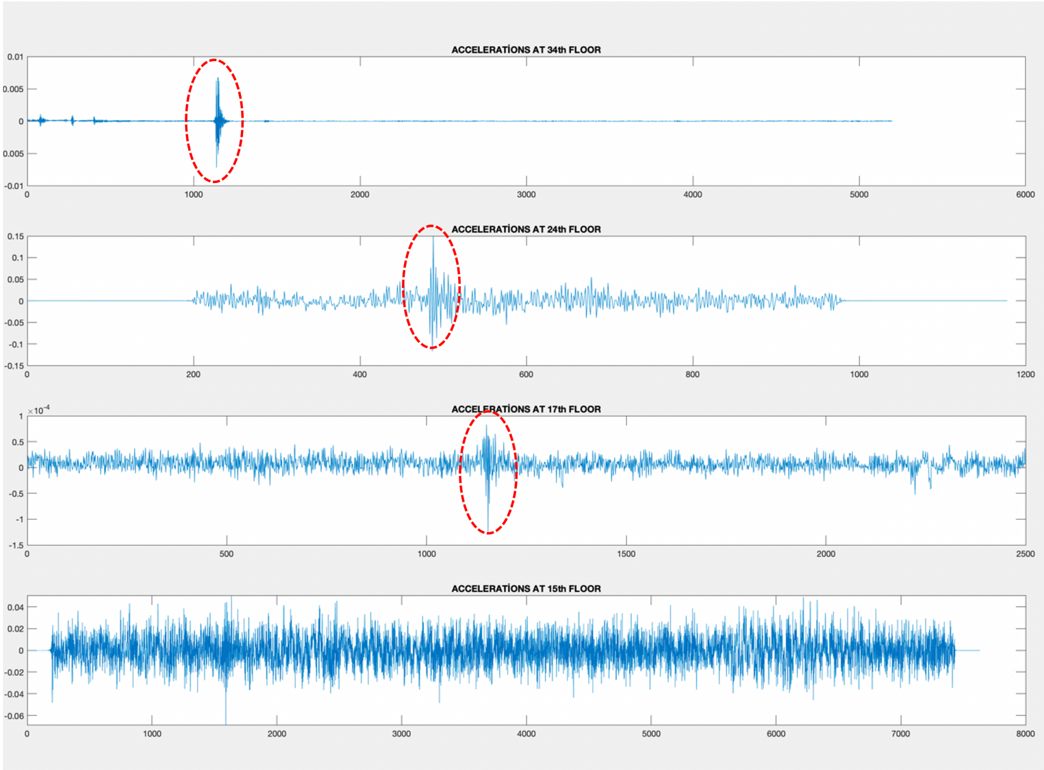


Figure 3. Downward propagation of the impulsive force given by the Impact Hammer at the 34th floor, and accelerations recorded at the 24th, 17th, and 15th floors. Note that impulse can be detected clearly at the 17th story, which is 17 story below the 34^{th} floor.

5. Utilization of IH data:

The Impact Hammer is used to identify the dynamic properties of each story of a multi-story building, as if they were a one-story structure. This is equivalent to assuming that a multi-story building is composed of one-story buildings put one on top of the other. By moving the impact generator from floor-to-floor and using the top-over-bottom spectral ratios of recorded story accelerations we can identify the dynamic characteristics of each story individually. The approach is based on the transfer-matrix formulation of the dynamic response. The details of the formulation and the system identification algorithm can be found in the paper by *Cetin and Safak* (2021), prepared within the RISE project and published recently in Earthquake Spectra.

In the paper, a multi-story building's response is formulated by using the transfer-matrix formulation, which considers the building as the superposition of one-story structures, put one on top of the other. Starting from the top story and going downward, each story's natural frequency and damping ratio are identified as it were a one-story building. A key requirement for this approach is to have vibration records from every story. Since this is typically not the case, we have developed methods to estimate the vibration time histories at non-instrumented floors from those of the instrumented floors (see, *Kaya et al,* 2015 and *Caglar and Safak*, 2022). The accuracy of these methods is confirmed by using real data from multi-story buildings instrumented at ever floor. Once vibration records are available at every floor, and starting from the top story, we can calculate the individual frequency and damping ratio of each story (i.e., as if it were a one-story building) by minimizing the error between the recorded and estimated Fourier Amplitude Spectra (FAS) of the vibration records in that story. The analytical models calibrated in this way are more accurate, and the structural system identified is unique. The *Cetin and Safak* paper presents numerical examples for the identification and show that the transfer-matrix based approach is superior to modal identification in terms of the insight it provides into the dynamic characteristics of the building.

We are currently developing methodologies to identify the characteristics of seismic wave propagation in multi-story buildings (e.g., wave travel times in each story, wave reflection and transmission coefficients at floor levels, and story damping) from the accelerations generated by the Impact Hammer. The approach is based on the theory developed in Safak (1999), which shows that wave propagation properties also provide a better insight into the dynamic characteristics of the building.

6. EMS Eccentric Mass Shaker

The objective in developing an EMS (Eccentric Mass Shaker) is to identify the resonant frequencies of buildings and surrounding soil, as well as to identify the presence of soil-structure interaction. The EMS designed to have two sets of four discs each rotating in opposite directions and generating a uni-directional sinusoidal horizontal force acting on the structure or soil surface at selected frequencies between 1 to 25 Hz. The amplitude of the sinusoidal force can be adjusted by adding or removing the masses in the shaker.

The key technical specifications of the Eccentric Mass Shaker are given in Figure 4, and the mechanical properties with pictures in Figure 5. The frequency and the force capacity of the Eccentric Mass Shaker for various combination of masses (i.e., the number of discs) are presented in Table 1, and the corresponding graphs in Figure 6.   More detail can be found in Appendix II.

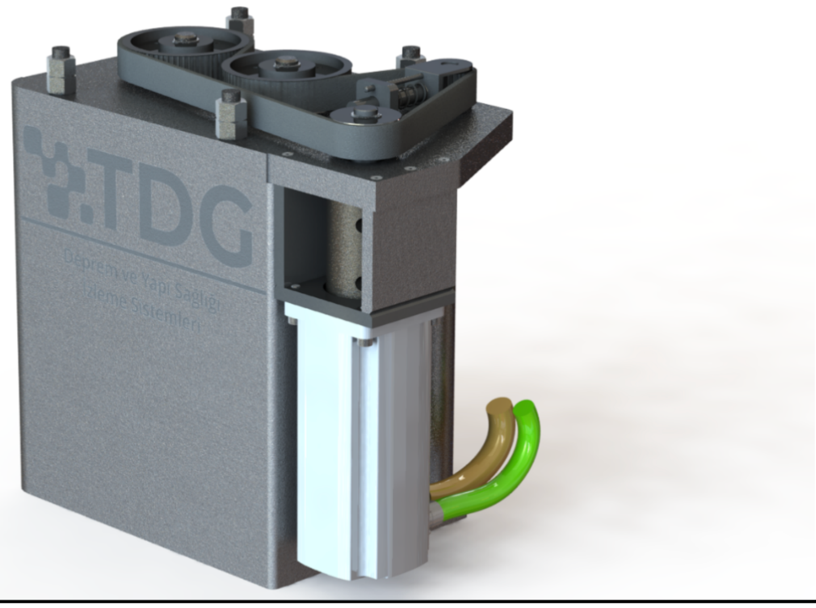
ECCENTRIC MASS SHAKER TECHNICAL SPECIFICATIONS	
ACTUATOR TYPE: **Schneider Servo Motor** BMH100 Series Maximum Revolution: 3000 rpm 	
TECHNICAL PROPERTIES	
Eccentricity Per Disc	0,181 kgm
Number of Discs	4 on each shaft, 8 in total
Mass Per Disc	4,2 kg
Maximum Force	1575 kgf
Axis of Force	Horizontal: X or Y (Depending on initial disc position)
Maximum Frequency	25 Hz
General Dimensions	Height: 440 mm Lenght: 250 mm Width: 470 mm
Total Weight	105 kg
Power Requirements	6 kW Single Phase 220 V AC

Figure 4. Technical properties of the Eccentric Mass Shaker.

MECHANICAL PROPERTIES

- Changeable force on X and Y axis (Depending on initial disc position)
- Strong floor mounting (M16 x 4)
- Total weight 105 kg
- Mass per disc 4,2 kg (Total 8 pieces)
- Servo motor with high precision frequency control
- 220 V AC Servo driver
- Mass can be add or remove
- 2 additional light-weight discs for high frequency operations
  (Eccentricity: 0,06 kgm, Weight: 1,659 kg)

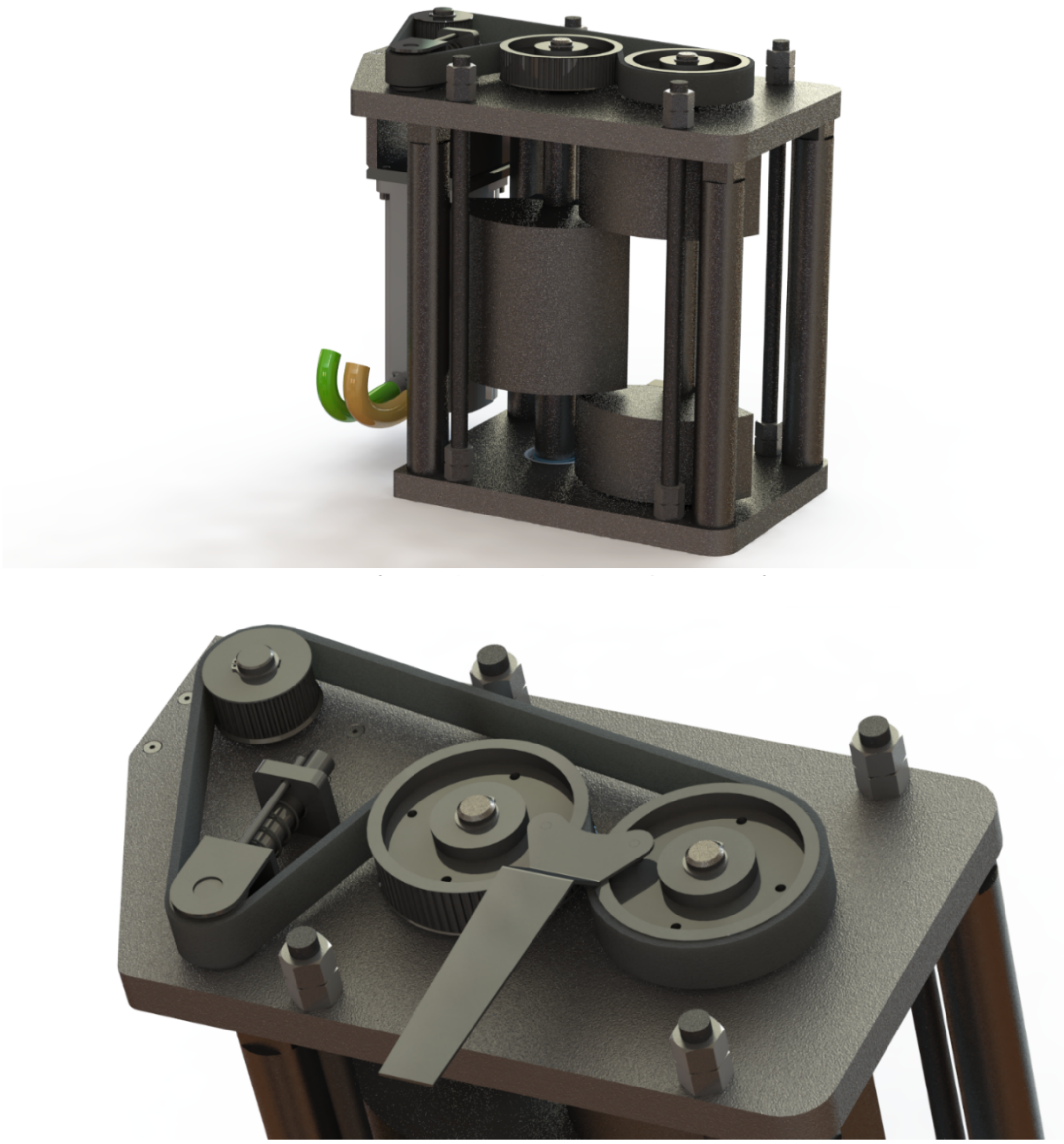


Figure 5. Mechanical properties of the shaker and belt-pulley mechanism.

Table 1 – Frequency and maximum force for various mass/discs configurations.

Frequency (Hz)	Maximum Number of Discs (n)	Maximum Force (kgf)
1	8	5,8
2	8	23,3
3	8	52,4
4	8	93,2
5	8	145,6
6	8	209,7
7	8	285,4
8	8	372,7
9	8	471,7
10	8	582,4
11	8	704,7
12	8	838,6
13	8	984,2
14	8	1141,4
15	8	1310,3
16	6	1118,1
17	6	1262,3
18	6	1415,1
19	6	1576,8
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24	2	838,6
25	2	909,9

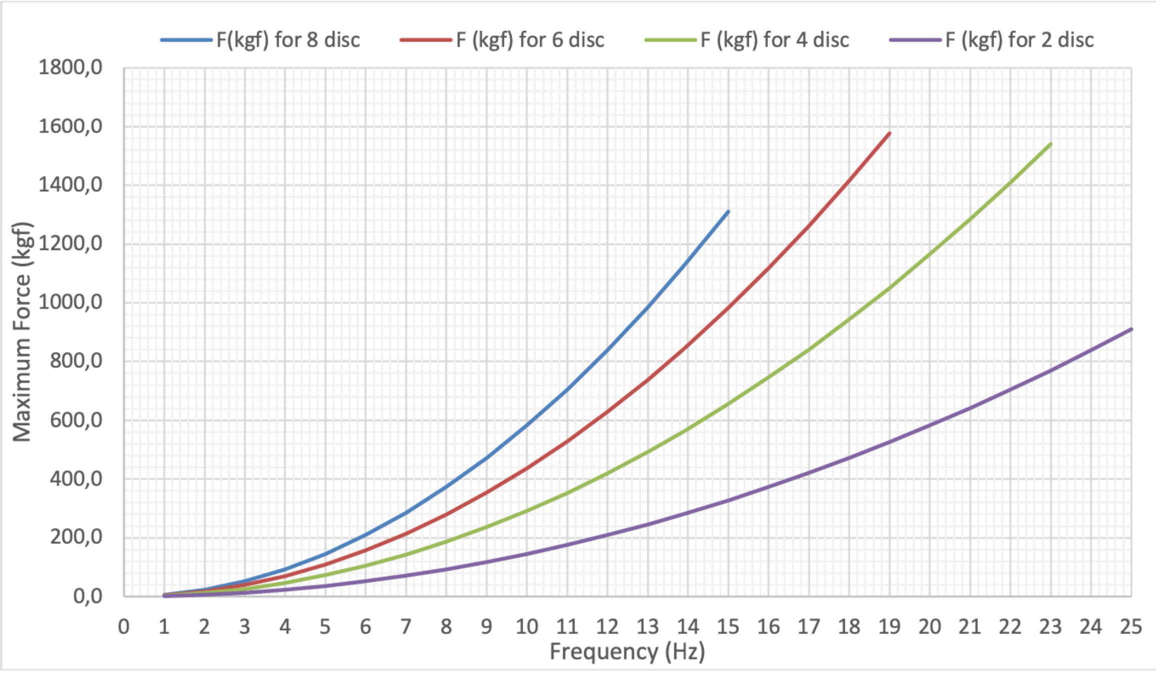


Figure 6. Variation of force with frequency of Eccentric Mass Shaker for various disc/mass configurations.

In order to utilize EMS for possible SSI (Soil-Structure Interaction) tests, we supplemented EMS with a thick base plate and metal stakes as schematically shown in Figure 7. The base plate is anchored to the soil near the building with eight thick and long metal stakes. The EMS is firmly attached to the base plate such that the horizontal force from the shaker is transferred to the soil to excite the soil near the building, and the building itself, so that we can see the characteristics of wave transmission from the soil to the building (i.e., SSI). Figure 8 shows the completed EMS with the base plate attached to the soil.

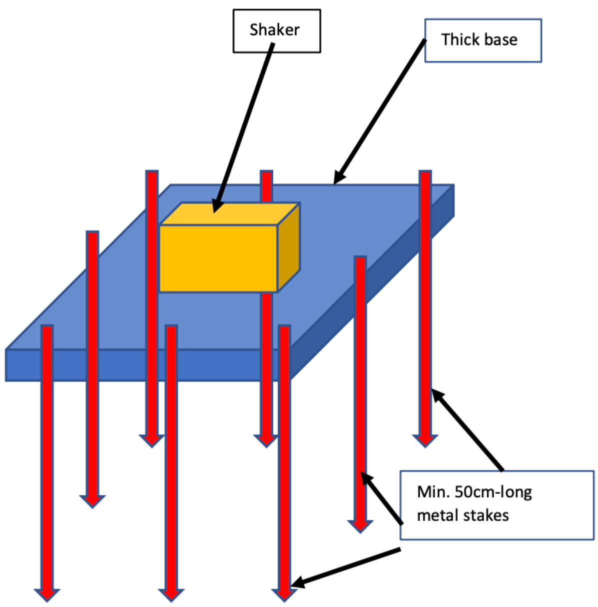


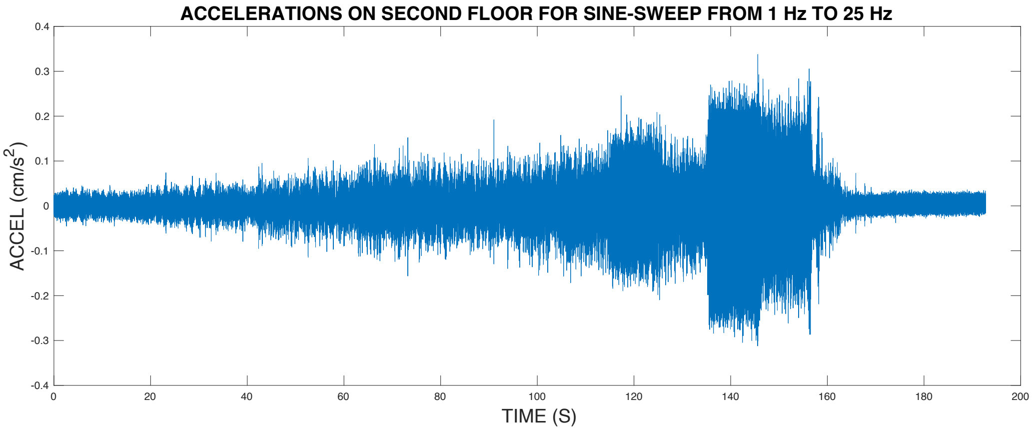
Figure 7. Schematic of Eccentric Mass Shaker and the base plate for soil-structure interaction tests.

Figure 8. Eccentric mass shaker with base plate attached to the ground for soil-structure interaction tests.

7. Examples of EMS data

EMS is very useful to identify the natural frequencies of short and stocky buildings, as well as the dominant frequencies of the soil surrounding the foundation. For buildings 7-10 stories and higher, ambient vibration data taken from the top are normally sufficient to identify dominant frequencies. For short buildings, or buildings where the data are available only from the lower floors, and for the ground, the ambient vibrations do not show the dominant frequencies because of very low signal-to-noise ratios.

Figure 9 shows the time-history and the corresponding FAS (Fourier Amplitudes Spectra) of a 2-story short and stocky building. The EMS is used to apply a sine-sweep excitation to the building from 1.0 Hz to 25 Hz. The corresponding FAS clearly shows the dominant frequency around 13 Hz.



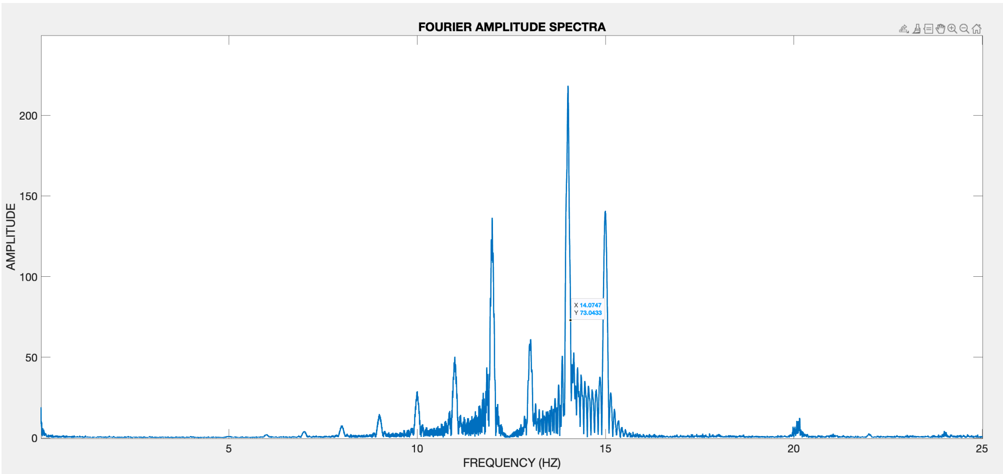


Figure 9. Response time-history and the corresponding FAS (Fourier Amplitudes Spectra) of a 2-story building to a sine-sweep excitation from 1 Hz to 25 Hz.

As an example to using EMS for soil-structure interaction tests, we have installed the EMS with its base plate 10 m away from a 2-story building, and applied a sine-sweep excitation from 1 Hz to 18 Hz to the ground surface. The configuration is shown in Fig. 10 below.

2.

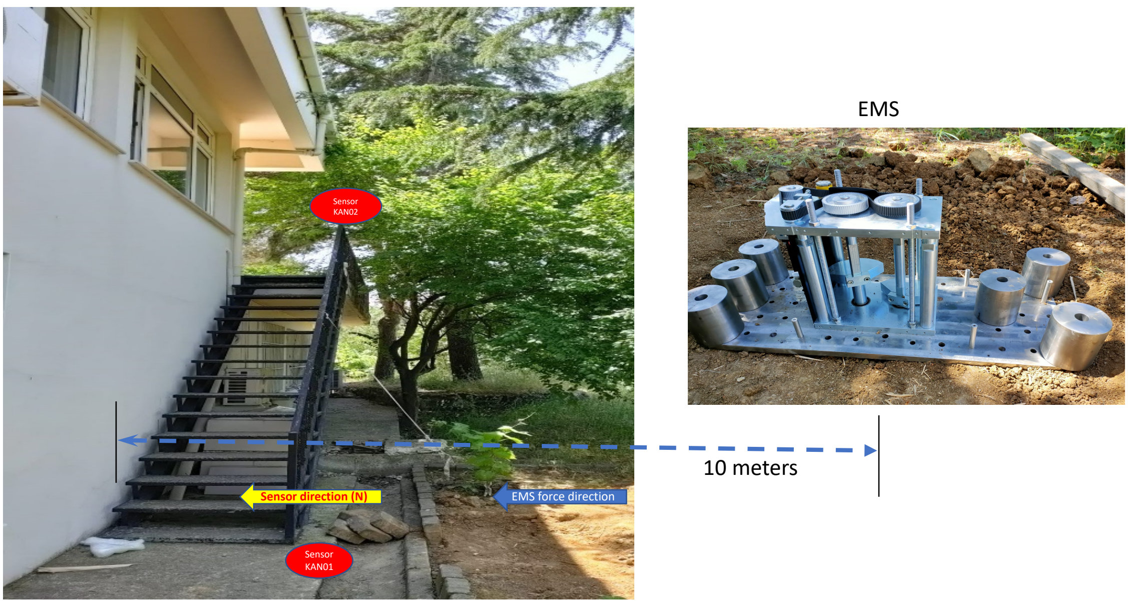


Figure 10. An example of using EMS for soil-structure interaction tests on a 2-story building to a sine-sweep excitation from 1 Hz to 18 Hz.

Fig. 11 shows the recorded accelerations on the ground surface near the building and the building's second story, and the corresponding Fourier Amplitude Spectra. The figures clearly show the dominant frequencies of the soil and the building.

It is important that the base plate of the EMS and the ground surface are fully coupled, i.e., no slippage or deformation of soil around the stakes. This will ensure that the force from the EMS is completely transferred to soil. For soft soil, soil deformations may be unavoidable. This can be minimized by using more and longer stakes.

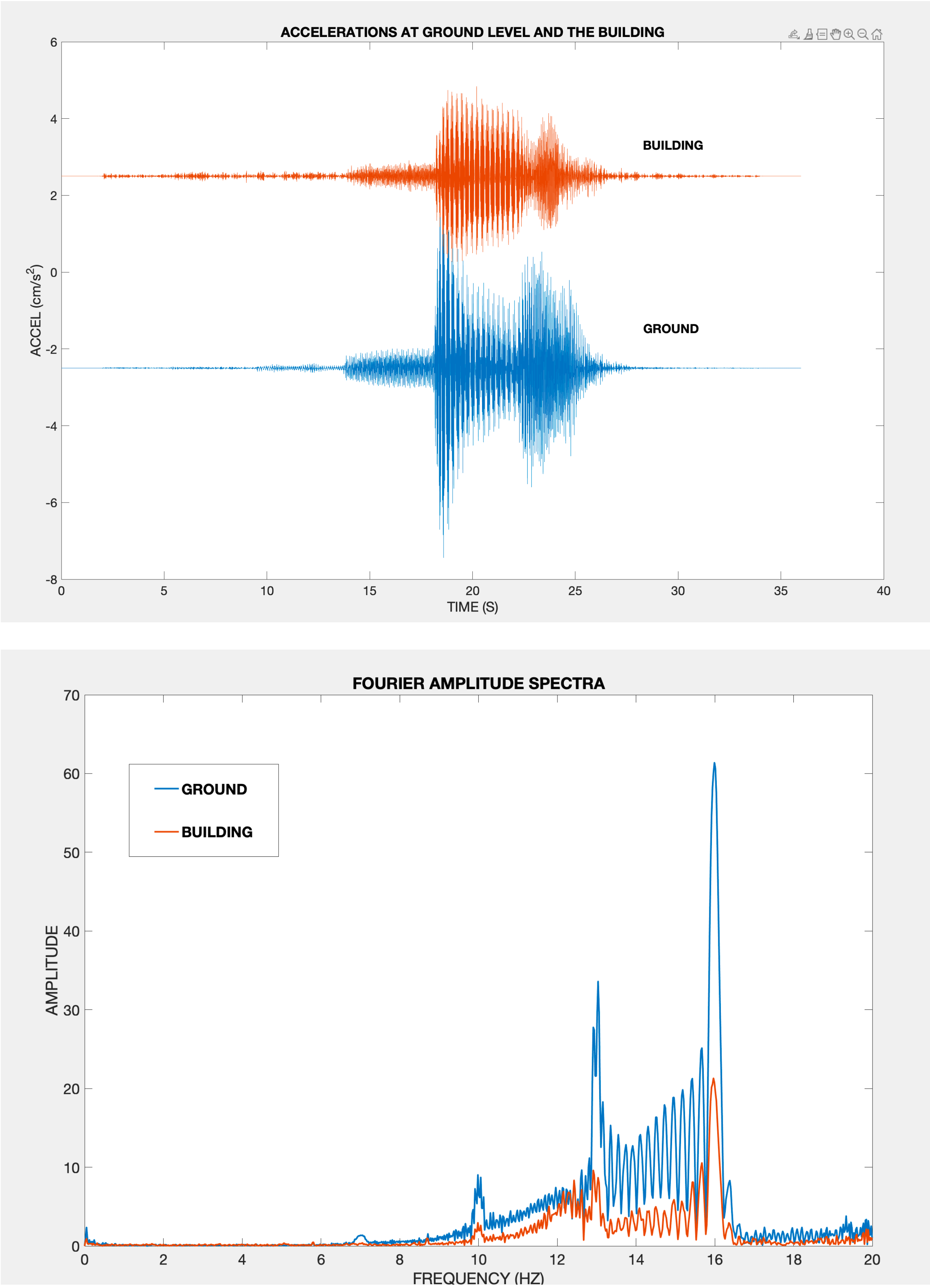


Figure 11. Time histories ogf the recorded accelerations on the ground surface and the 2nd story of the building.

References

The references related to utilization of IH and EMS data are given below. The last two papers (4 and 5) are completed during the BOUN's work within the RISE project and RISE's contribution is acknowledged in both.

1. Şafak,E.(1995).Detection and identification of soil-structure interaction in buildings from vibration recordings, *Journal of Structural Engineering*, ASCE, Vol.121, No.5, May 1995, pp.899-906.
2. Safak, E. (1999). Wave propagation formulation of seismic response of multi-storybuildings, *Journal of Structural Engineering*, ASCE, Vol. 125, No. 4, pp.426-437.
3. Kaya, Y ., S. Kocakaplan, and E. Şafak (2015). System identification and model calibration of multi-story buildings through estimation of vibration time histories at non- instrumented floors. *Bulletin of Earthquake Engineering 13(11)*, 3301–3323.
4. Cetin M, and E. Safak (2021) . An algorithm to calibrate analytical models of multi-story buildings from vibration records, *Earthquake Spectra, 1–17, DOI: 10.1177/87552930211046969.*
5. Caglar, N.M. and E. Safak (2022). Estimation of the response of non-instrumented floors using the Timoshenko and Bernoulli-Euler Beam Theories, *Earthquake Engineering & Structural Dynamics*, 2022, Vol.1, No.3, DOI: 10.1002/eqe.3636

Appendices

I - Detailed Design Drawings of Impact Hammer
II – Technical Document for Eccentric Mass Shaker
III – Instrumented Buildings

APPENDIX I: IMPACT HAMMER

The design drawings and the pictures for its use of the impact hammer are given below. It involves four springs, a lever to set the springs, and a release button. It can transfer the impulsive force to the floor by connecting the hammer to the floor, or to a wall or column by placing it against them.

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MEKANİK DARBE ÇEKİCİ TEKNİK ÖZELLİKLER

MEKANİK DARBE ÇEKİCİ TEKNİK ÖZELLİKLERİ

Momentum Capacity (kgxm/s)	100
Impact mass (kg)	80
Maximum contraction (mm)	54
Impact area (mm²)	31400
Maximum Velocity (mm/s)	1250 mm/s
Number of springs	4
Maximum force need for setting the springs (N)	~2000 N = 200 kg
Maximum height (mm)	430
Maximum width (mm)	466
Maximum length (mm)	~1000

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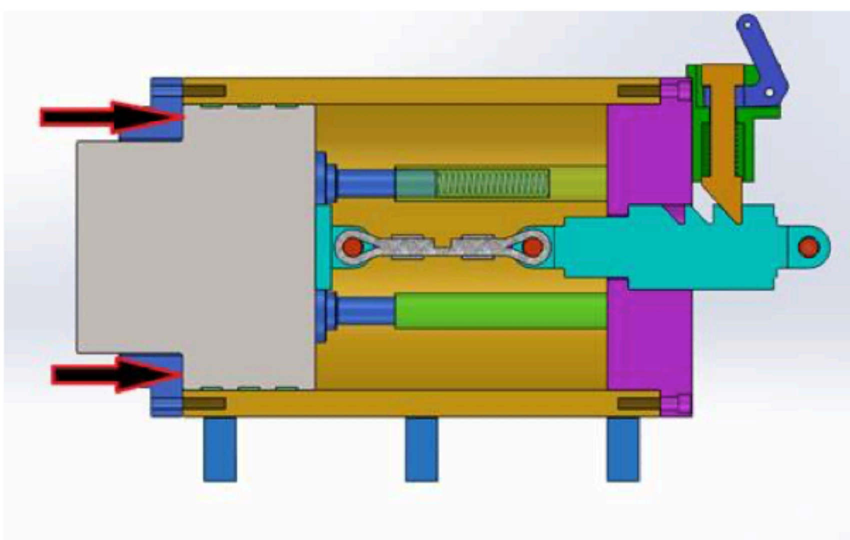

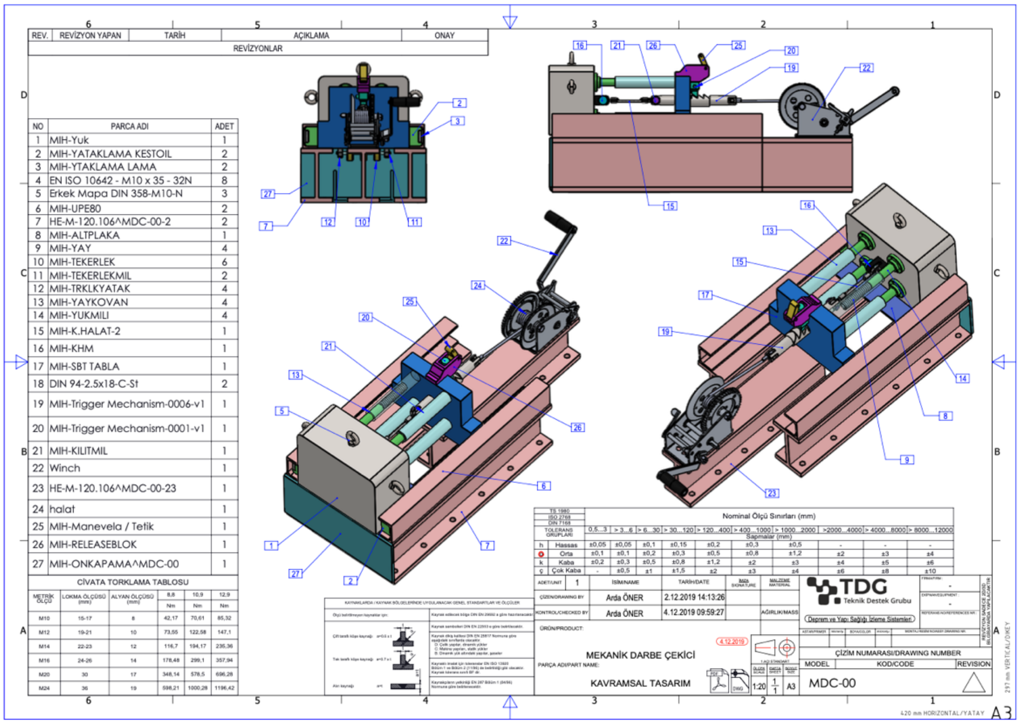
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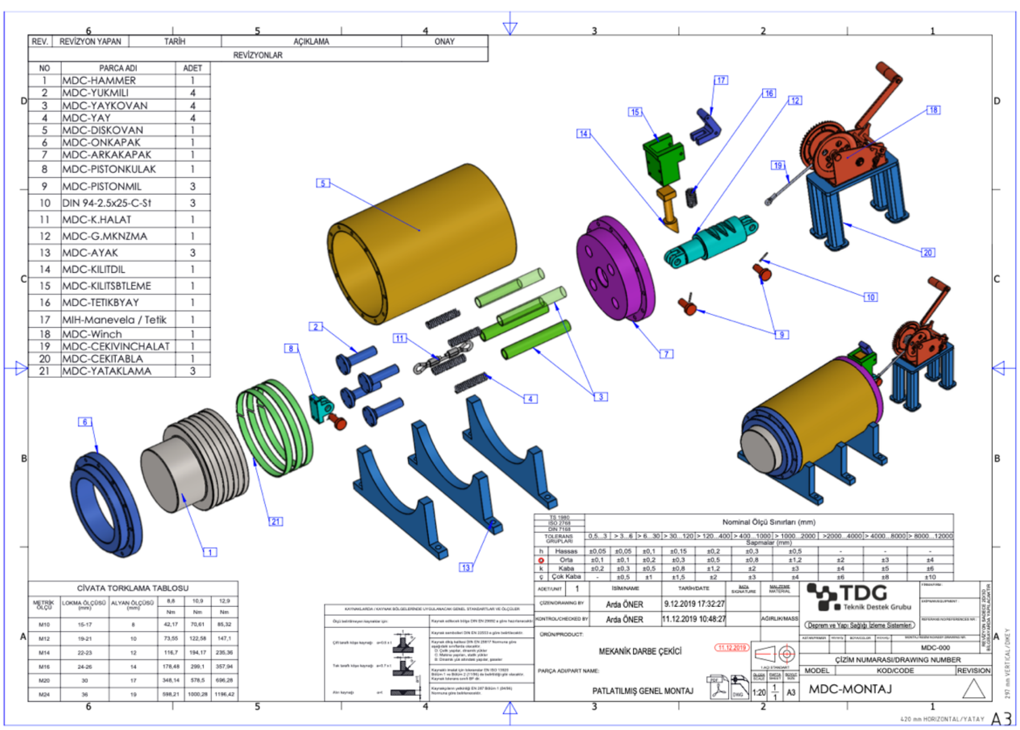
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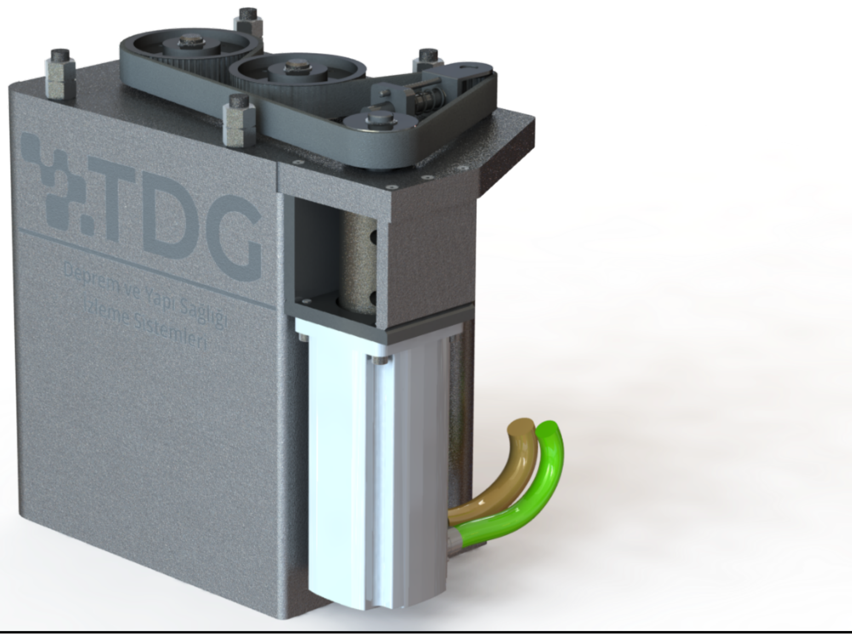
TDG

Servo Hidrolik ve Elektro-Mekanik Çözümler

ECCENTRIC MASS SHAKER TECHNICAL DOCUMENT

ECCENTRIC MASS SHAKER TECHNICAL SPECIFICATIONS

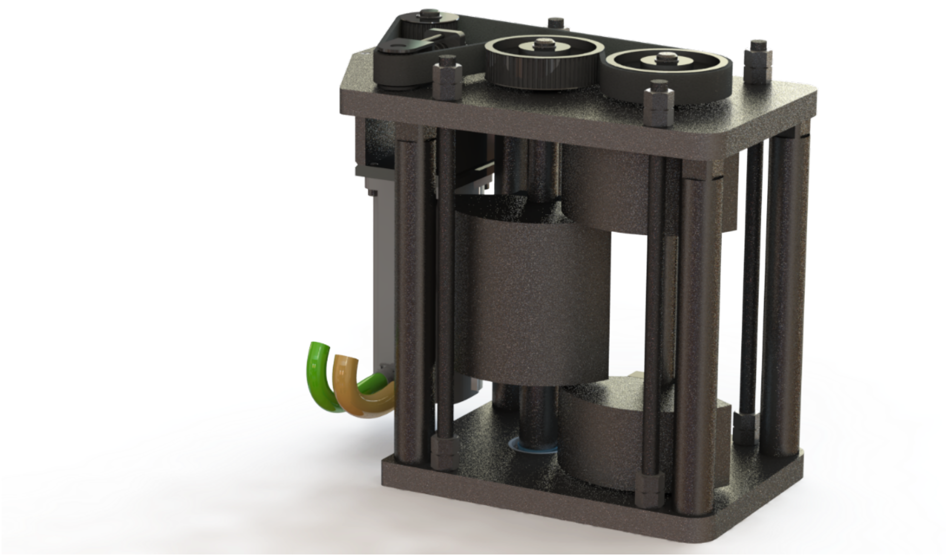
ACTUATOR TYPE:
Schneider Servo Motor
BMH100 Series
Maximum Revolution: 3000 rpm



TECHNICAL PROPERTIES	
Eccentricity Per Disc	0,181 kgm
Number of Discs	4 on each shaft, 8 in total
Mass Per Disc	4,2 kg
Maximum Force	1575 kgf
Axis of Force	Horizontal: X or Y (Depending on initial disc position)
Maximum Frequency	25 Hz
General Dimensions	Height: 440 mm Lenght: 250 mm Width: 470 mm
Total Weight	105 kg
Power Requirements	6 kW Single Phase 220 V AC

MECHANICAL PROPERTIES

- Changeable force on X and Y axis (Depending on initial disc position)
- Strong floor mounting (M16 x 4)
- Total weight 105 kg
- Mass per disc 4,2 kg (Total 8 pieces)
- Servo motor with high precision frequency control
- 220 V AC Servo driver
- Mass can be add or remove
- 2 additional light-weight discs for high frequency operations (Eccentricity: 0,06 kgm, Weight: 1,659 kg)



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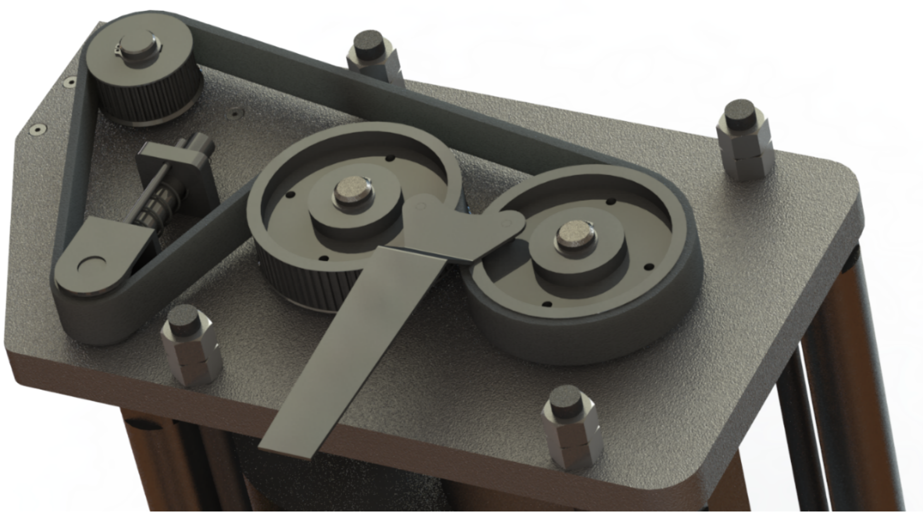
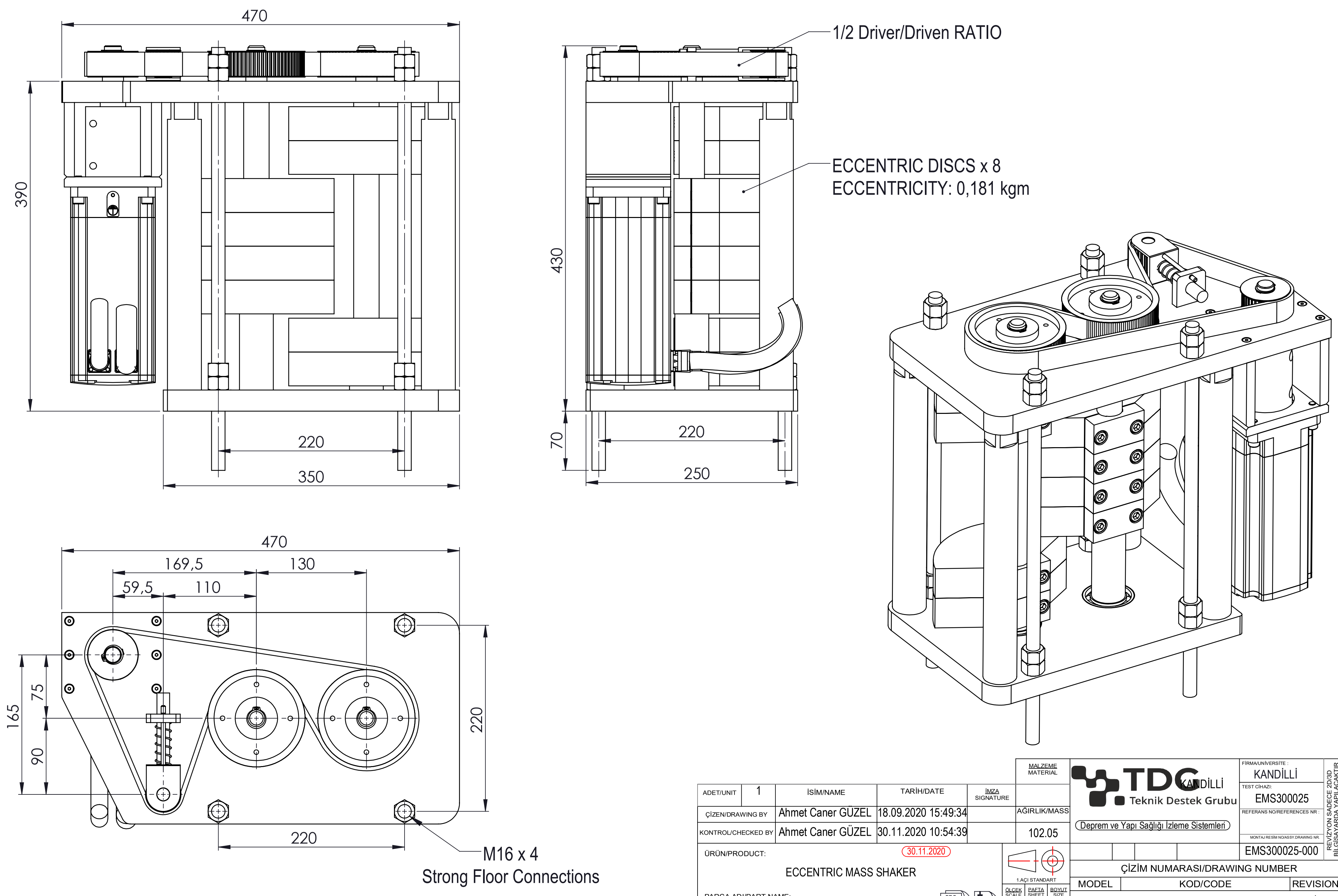


(Sample Belt-Pulley Mechanism)



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ÜRÜN/PRODUCT: ECCENTRIC MASS SHAKER

30.11.2020

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297 mm VERTICAL/DİKEY

420 mm HORIZONTAL/YATAY A3

FREQUENCY AND FORCE CAPACITY

Frequency (Hz)	Maximum Number of Discs (n)	Maximum Force (kgf)
1	8	5,8
2	8	23,3
3	8	52,4
4	8	93,2
5	8	145,6
6	8	209,7
7	8	285,4
8	8	372,7
9	8	471,7
10	8	582,4
11	8	704,7
12	8	838,6
13	8	984,2
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22	4	1409,3
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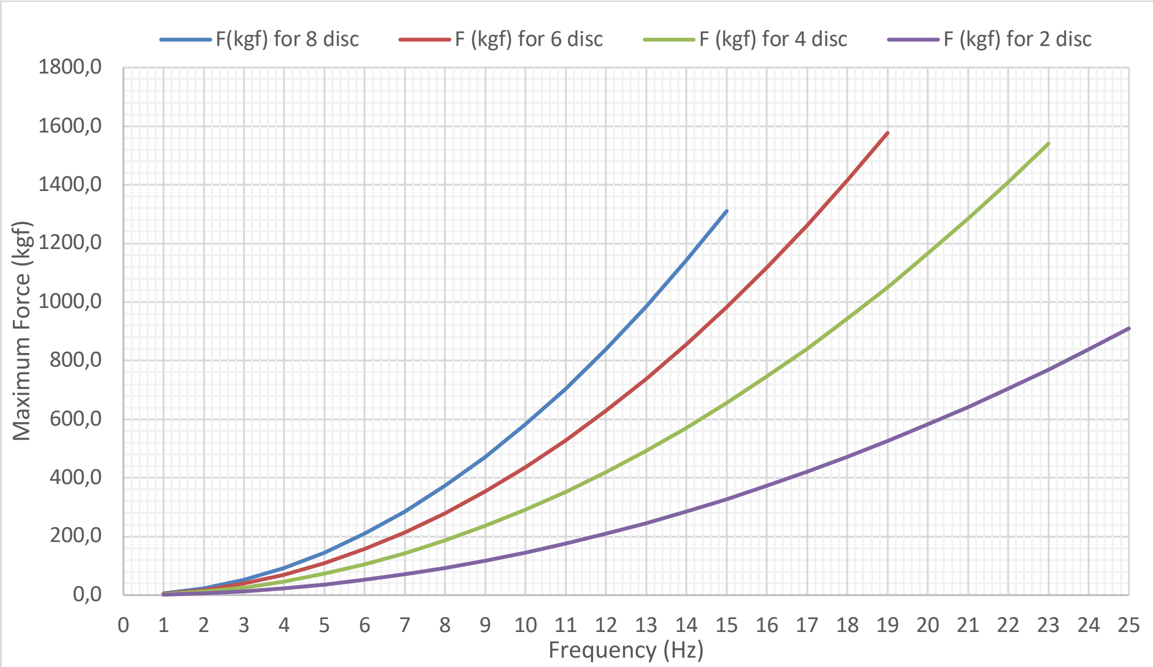
24	2	838,6
25	2	909,9

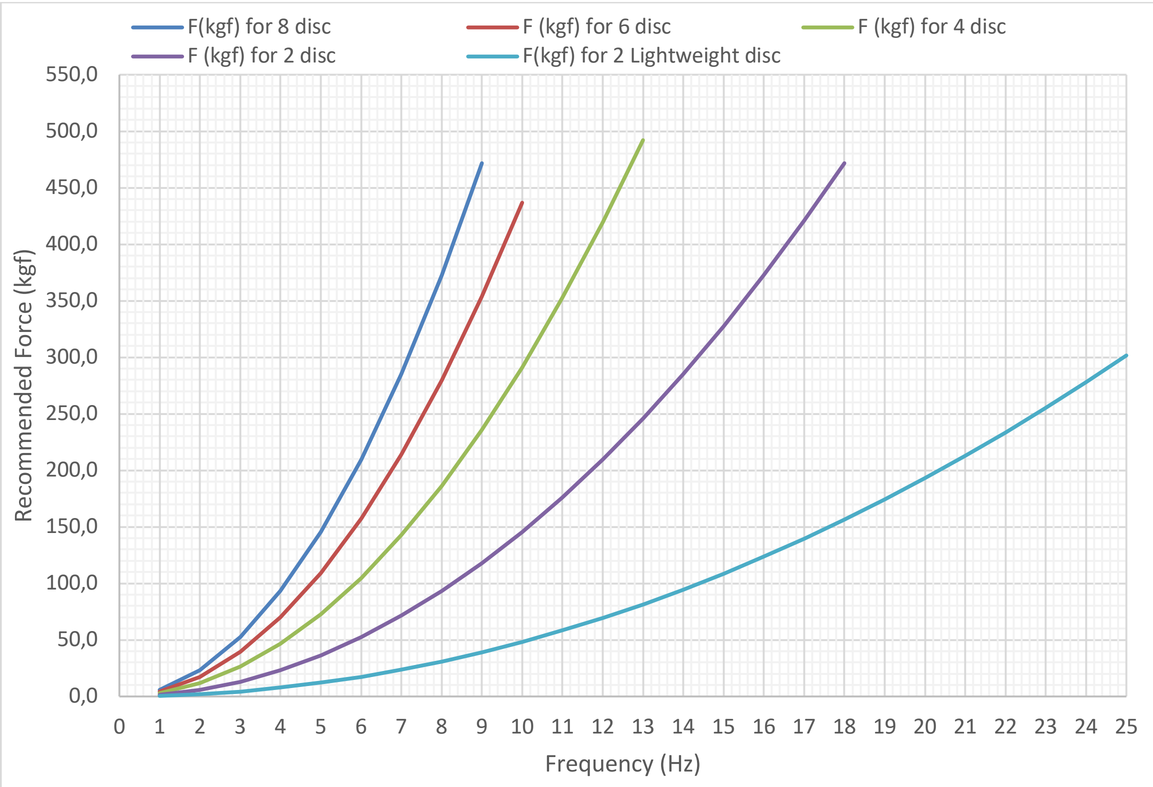
(Table-1)

Frequency (Hz)	Recommended Number of Discs (n)	Recommended Force (kgf)
1	8	5,8
2	8	23,3
3	8	52,4
4	8	93,2
5	8	145,6
6	8	209,7
7	8	285,4
8	8	372,7
9	8	471,7
10	6	436,8
11	6	528,5
12	4	419,3
13	4	492,1
14	2	285,4
15	2	327,6
16	2	372,7
17	2	420,8
18	2	471,7
19	2	525,6
20	2 (Light-Weight)	193,0
21	2 (Light-Weight)	212,8
22	2 (Light-Weight)	233,6
23	2 (Light-Weight)	255,3
24	2 (Light-Weight)	278,0
25	2 (Light-Weight)	301,6

(Table-2)



(Graph-1)



(Graph-2)

APPENDIX III. TEST BUILDINGS

1. Sapphire Building in Istanbul, Turkey

2. Project partner/s:
BOUN

3. Location:
Istanbul, Turkey, 41.08471 N, 29.00622 E

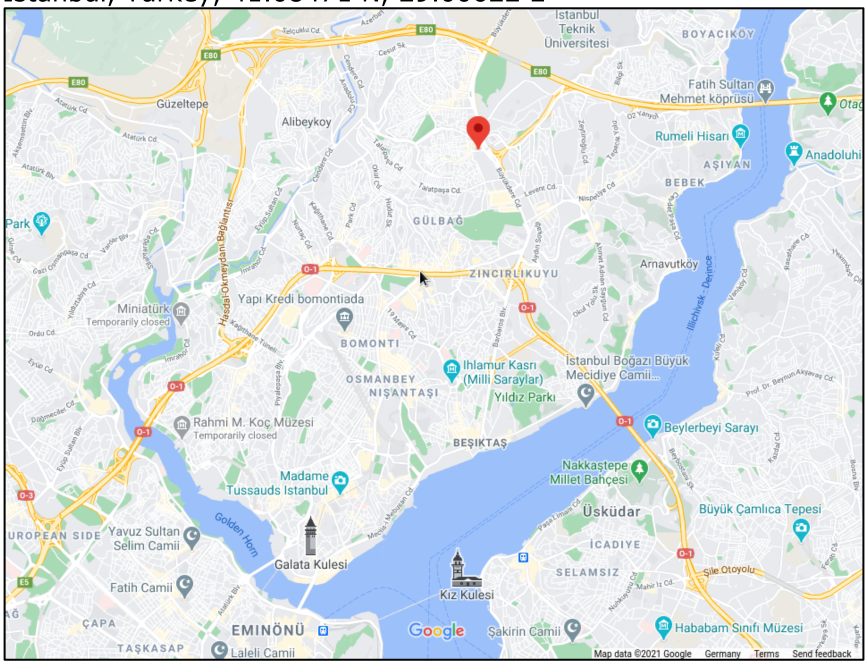


Fig. 1 Location of the instrumented Sapphire building in Istanbul, Turkey (image from Google Maps).

Fig. 2 View of the Sapphire building in Istanbul, Turkey (image from CTBUH's The Skyscraper Center).

4. Description of the building:

a) Number of storeys above ground level: 55
b) Number of storeys below ground level: 10
c) Occupancy: residential and commercial
d) Year of construction: 2006-2010
e) Lateral load-resisting system:

	Direction X	Direction Y
Reference	E-W	N-S
Material	RC	RC
System	Shear walls + Frames	Shear walls + Frames

f) Floor system: Reinforced concrete, cast-in-place
g) Shape of the building plan: Rectangular
h) Material of exterior walls: Glass cladding
i) Roof: RC flat roof
j) Foundation system: Mat foundation
k) Foundation soil: Stiff soil

5. Description of the sensors:

Guralp 5TC sensors (see: https://www.guralp.com/documents/DAS-050-0004.pdf)

6. Location of the sensors in the building:

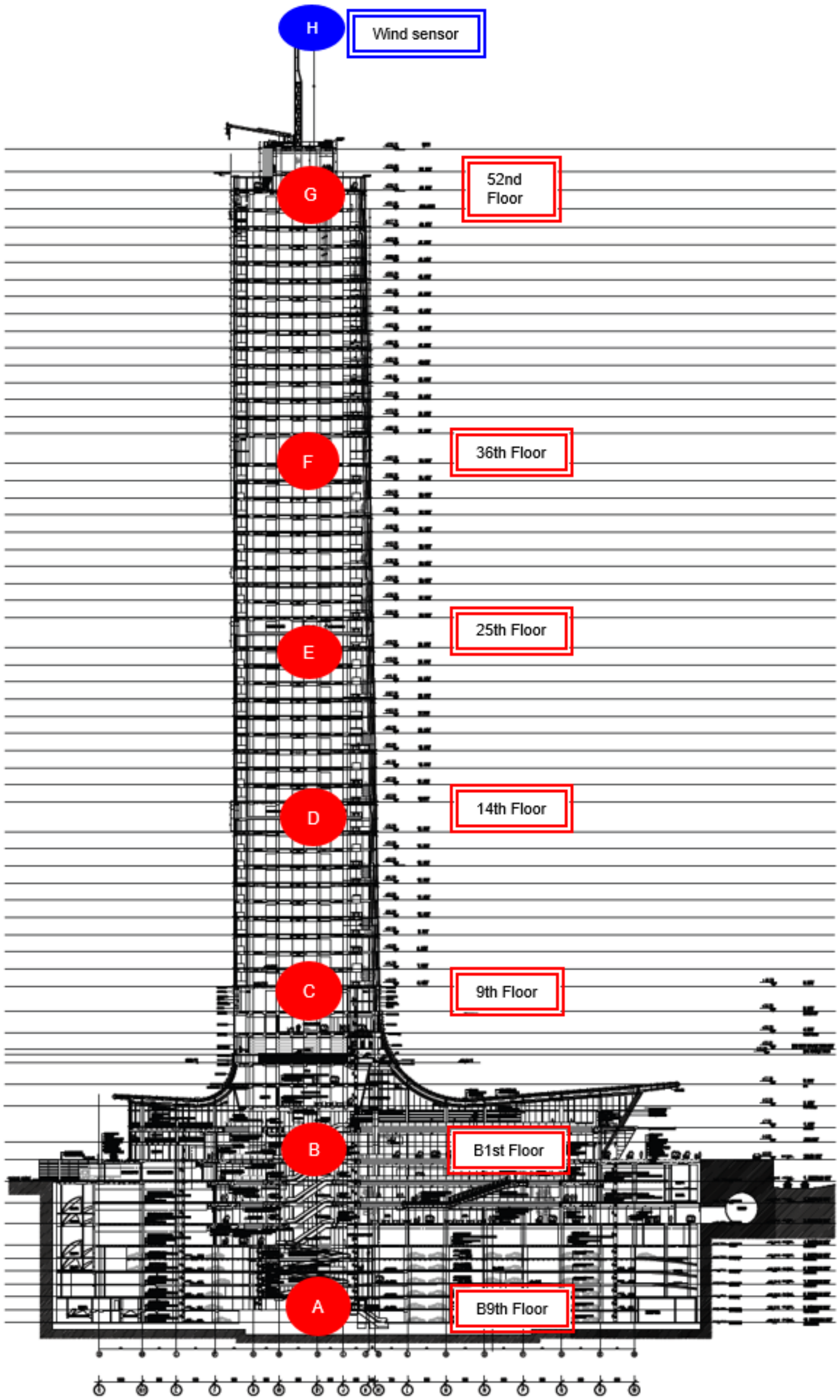


Fig. 3. Location of sensors in the Sapphire building in Istanbul, Turkey.

Location of sensors and floor plan:

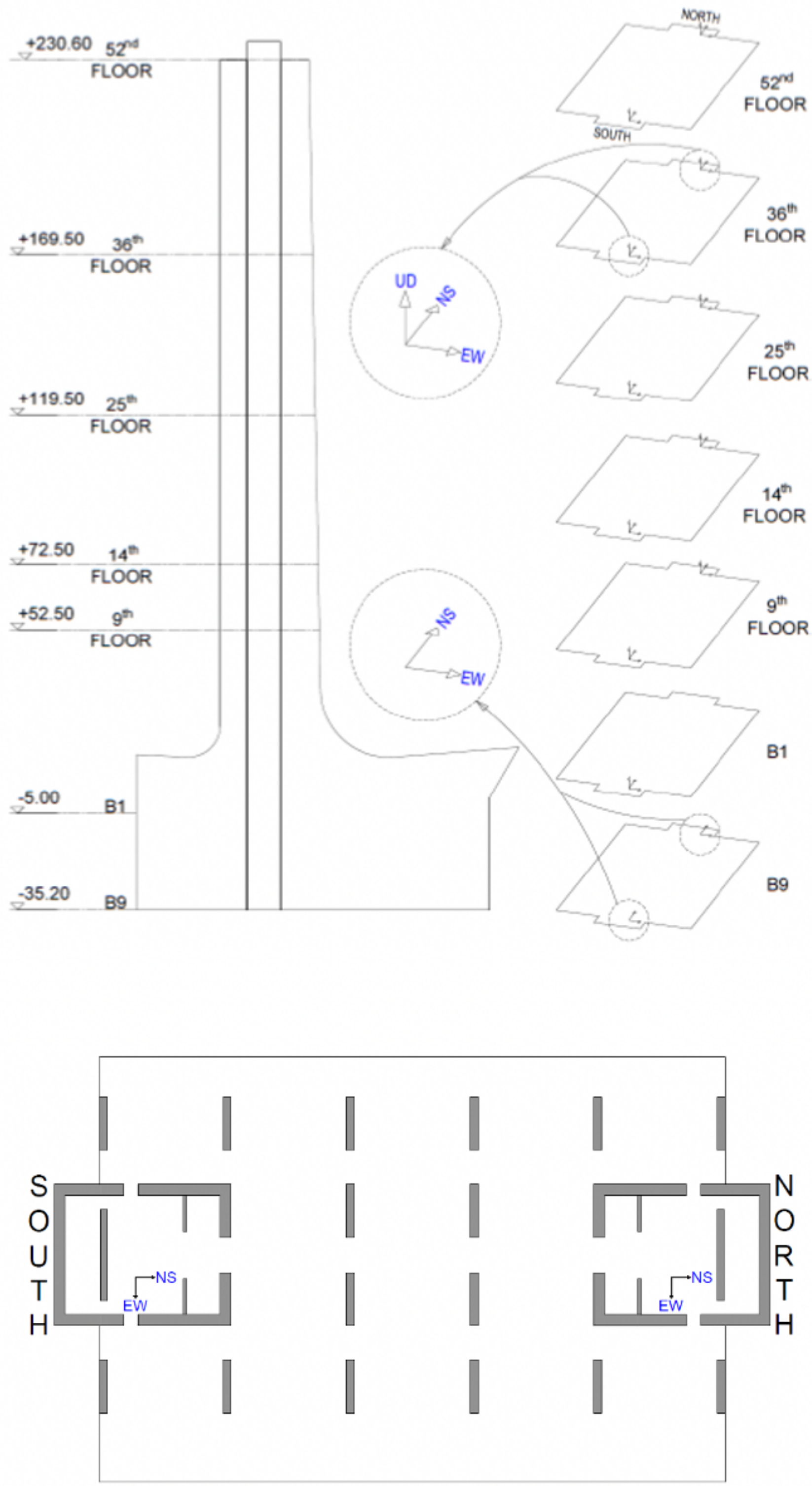


Fig. 4 Location of the sensors in the Sapphire building (vertical elevation and plan view).

7. **Date of installation of sensors:**
   Continuous recordings at 200 Hz since 2010 are available.

8. **Duration of the monitoring activities:**
   Permanent, continuous.

9. **Data collection and storage:**
   a) Continuous streaming, stored in a central server.
   b) Guralp CGF format.

10. **Excitation:**
    Ambient forces, wind, earthquake (continuous recording).

11. **Building state:**
    Well maintained.

12. **Processing of the raw waveforms:**
    In-house tools and software

13. **Processing of the pre-processed waveforms to obtain dynamic response parameters of interest, if applicable:**
    Parameters/dynamic properties are being calculated in real-time using in house prepared software.

14. **Data availability:**
    On demand, need permission from the owner.

2. Polat Tower in Istanbul, Turkey

1. **Project partner/s:**
   BOUN

2. **Location:**
   Istanbul, Turkey, 41°-03′N, 28^0-59′E

Fig. 5. View of the instrumented Polat tower in Istanbul, Turkey.

3. **Description of the building:**
   a) Number of storeys above ground level: 34
   b) Number of storeys below ground level: 6
   c) Occupancy: Residential
   d) Year of construction: 2001
   e) Lateral load-resisting system:

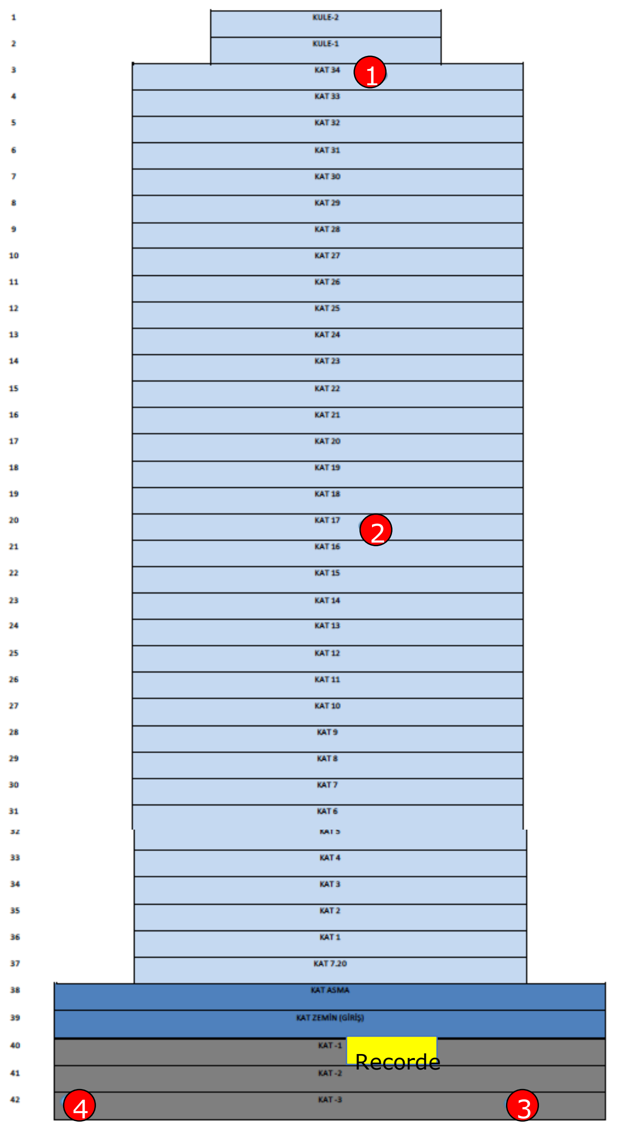
	Direction X	**Direction Y**
Reference	E-W	N-S
Material	RC	RC
System	RC Shear walls+Frames	RC Shear walls+Frames

f) Floor system: reinforced concrete? RC Cast-in-place
g) Shape of the building plan: Rectangular
h) Material of exterior walls: Glass cladding
i) Roof: RC Flat roof
j) Foundation system: Mat foundation
k) Foundation soil: Stiff soil

4. Description of the sensors:

Guralp GMG accelerometer (see: https://www.guralp.com/documents/MAN-050-0001.pdf)

5. Location of the sensors in the building:



POLAT TOWER MONITORING SYSTEM:

- 12 Channels; 4 tri-axial accelerometers at four locations
- Synchronized, real-time recording at 200 Hz.

Fig. 6. Location of the sensors in the Polat tower (vertical elevation).

6. **Date of installation of sensors:**

   2013

7. **Duration of the monitoring activities:**

   In 2013-2014 Triggered based; 2015 and afterwards continuous.

8. **Data collection and storage:**
   a) Continuous streaming, data stored in a central server
   b) Geosig DAT format

9. **Excitation:**
   - Ambient vibrations, wind, earthquakes; continuous recording.
   - Excitation with impact hammer and eccentric mass shaker.

10. **Building state:**

    Well maintained.

11. **Processing of the raw waveforms:**

    In-house software

12. **Processing of the pre-processed waveforms to obtain dynamic response parameters of interest, if applicable:**

    Parameters/dynamic properties are being calculated using in-house tools and software.

13. **Data availability:**

    Available on demand with the owner's permission.