ENVIRONMENTAL GEOSCIENCES

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Lecture-57

Geophysical Methods, Gravity Methods

Welcome to the SWAYAM NPTEL course on Environmental Geosciences. We are discussing the module eleven. We have already discussed the lecture one and lecture two. Now today we will discuss the lecture three that is Geophysical Methods and Gravity Methods. The important concepts will be covered in this lecture are, introduction to geophysics, introduction to geophysical methods, introduction to gravity methods, Newton's law of gravitation, acceleration of gravity, gravity of the earth that is density of rocks and minerals, gravity instruments and application of the gravity method.

Geophysics is the branch of earth science that applies principle of physics to study the Earth's structure, composition and dynamic processes. It involves the measurement and interpretation of physical properties such as gravity, magnetism, seismic waves, electrical conductivity, and heat flow to understand subsurface conditions. It plays a crucial role in various fields including mineral and petroleum exploration, environmental studies, engineering, and natural hazard assessment. It is the subsurface site characterization of the geology, geological structure, groundwater contamination, and human artifacts beneath the Earth's surface based on the lateral and vertical mapping of physical property variations that are remotely sensed using non-invasive technology. These technologies are traditionally used for exploration of economic materials such as groundwater, metals and hydrocarbons.

It is the non-invasive investigation of subsurface conditions in the earth through measuring, analyzing and interpreting physical fields at the surface. Some studies are used to determine what is directly below the surface; other investigations extend to depths of tens of meters or more. It is the application of method of physics to study of the Earth. The rock does not differ only by their macroscopic or microscopic properties studied by field geologists or petrologists. They also differ by their chemical and physical properties. Hence as the rocks differ according to their origin, structure, texture etc. They also differ by their density, magnetization, resistivity etc. Now introduction to geophysical methods. The continued expansion in the demand for metals and petroleum products have led to the development of many geophysical techniques for the detection and mapping of unseen deposits and structures.

The great majority of mineral deposits are beneath the surface, their detection depends on those characteristics that differentiate them from the surrounding media. Methods based on variations in the elastic properties of rocks have been developed for determining structures associated with oil and gas, such as faults, anticlines, synclines, several kilometers below the surface. The variation in electrical conductivity and natural currents in the earth, rates of decay of artificial potential differences introduced into the ground, local changes in gravity, magnetism and radioactivity- all these provide information about the nature of the structures below the surface. The search for coal, oil and gas is confined to sedimentary basins except for rare instances in which oil or gas has migrated into fractured igneous or metamorphic rocks. Applied geophysics in the search for minerals, oil and gas may be divided into different methods of exploration, which are as follows.

You can see here gravity methods, magnetic methods, seismic methods, electrical methods, electromagnetic methods, radioactivity methods, well logging methods, chemical methods and thermal methods. The choice of techniques to locate a certain mineral depends on the nature of the mineral and of the surrounding rocks. For example, the magnetic method is used in petroleum exploration as a reconnaissance tool to determine the depth to the basement rocks and thus determine where the sediments are thick enough to warrant exploration. Seismic exploration is another method that has been used to explore large areas both on land and offshore, though at considerably greater cost, in both time and money. Now, introduction to gravity methods.

Gravity methods are geophysical techniques used in mineral exploration to detect variations in the Earth's gravitational field caused by differences in rock density. This method is based on the principle that denser rock formations exert a stronger gravitational pull than less dense materials. By measuring these subtle variations in gravity, geologists can infer the presence of subsurface mineral deposits, ore bodies or geological structures associated with valuable resources. Gravity methods, though fundamentally dependent upon topography, latitude, and composition of the Earth, variations obtained in the value of gravity and measured at the surface are also caused by irregularity in the distribution of rocks of different densities. The gravimetric survey based on the measurement of density contrasts between the anomaly producing body and the surrounding rock. It involves measurements of variations in the gravitational field of the Earth.

One hopes to locate local masses of greater or lesser density than the surrounding formations and learn something about them from the irregularities in the Earth's field. Gravity prospecting is used as a reconnaissance tool in oil exploration, although expensive, it is still considerably cheaper than seismic prospecting. In mineral exploration, gravity prospecting usually has been employed as a secondary method, although it is used for detailed follow-up of magnetic and electromagnetic anomalies during integrated base metal surveys. Gravity surveys are sometimes used in engineering and archaeological studies. Like magnetics, radioactivity and some electrical techniques, gravity is a natural source method.

Local variations in density of rocks near the surface cause minute changes in the gravity field. Gravity is an inherent property of mass. Density variations are relatively small and the gravity effects of local masses are very small compared with the effect of background field of the earth as a whole. The time variation of the gravity field is constant. Corrections to gravity readings are more complicated and more important than any other geophysical methods.

Gravity field operations are more expensive and field work is slower and requires more highly skilled personnel. Newton's Law of Gravitation. The force of gravitation is expressed by the Newton's law. The Newton's law states the force between two particles of masses m_1 and m_2 is directly proportional to the product of masses and inversely proportional to the square of the distance between the center of the mass.

$$F = \gamma \left(\frac{m_1 m_2}{r^2}\right) r_1$$

So here is the equation in which F is the force on m_2 by m_1. r_1 is the unit vector directed from m_2 toward m_1. Small r is the distance between m_1 and m_2. γ is the universal gravitational constant. The force F is always attractive. In SI units, the value of γ is 6.67×10^{-11} N-m^2/kg^2.

Or in cgs unit, it is 6.67×10^{-8} dyne-cm^2/g^2. Now, acceleration due to gravity. The acceleration due to gravity on Earth is the force that pulls objects towards the planet's center. It is a fundamental aspect of physics that governs the motion of objects and plays a crucial role in various natural and scientific phenomena. Gravity is caused by the Earth mass which generates an attractive force on all objects.

Gravity varies across Earth's surface due to several factors. The planet's rotation causes a slight reduction in gravity at the equator compared to the poles. Additionally, gravity decreases with altitude as the distance from Earth's center increases. Beneath the surface, gravity also changes depending on depth as only the mass enclosed within that depth contributes to the gravitational force. Local variations in Earth's gravity occur due to differences in geological formations, density variations in Earth's interior and topographical features.

These variations can be studied using gravitational surveys which help in understanding Earth's structure and detecting mineral deposits or underground reservoirs. Gravity influences many aspects of daily life and scientific exploration. It determines the motion of falling objects, controls ocean tides, and affects the orbits of satellites and space missions. It also plays a key role in planetary motion and astrophysics governing the interaction between celestial bodies. Understanding gravity is essential in engineering, aviation, space exploration and geophysics as it helps in designing structures, predicting planetary movements and launching spacecraft into orbit.

The acceleration of gravity was first measured by Galileo in his famous experiment at Pisa. The numerical value of g at the Earth's surface is about 980 cm/s^2. In honor of Galileo, the unit of acceleration of gravity that is 1 cm/s^2 is called the Galileo or Gal. Graviometers used in field measurements have a sensitivity of about 10^{-5} Gal or 0.01 mGal, although the reading accuracy is generally only 0.03 to 0.06 mGal. As a result, they are capable of distinguishing changes in the value of g with a precision of one part in ten to the power eight. Microgravimeters are available with measuring accuracy of about 5 μGal.

Gravity of the earth, and densities of rocks and minerals. The quantity to be determined in gravity exploration is local lateral variation in density. Generally, density is not measured in situ, although it can be measured by borehole logging tools. Density can also be estimated from seismic velocity. Often density measurements are made in the laboratory on small outcrop or drill core samples.

However, laboratory results rarely give the true bulk density because the samples may be weathered, fragmented, dehydrated, or altered in the process of being obtained. Consequently, density is often not very well known in specific field situations. Sedimentary rocks are usually less dense than igneous and metamorphic rocks. The wide range of density of sedimentary rock is primarily due to variation in porosity The nature of poor fluids also affects the bulk density.

Sedimentary rock density is also influenced by age, previous history, and depth of burial. Obviously, a porous rock will be compacted when buried. Density increases with depth and time. The density contrast between adjacent sedimentary formations in the field is seldom greater than zero point two five gram per centimeter cube. Although igneous rocks generally are denser than sedimentary rocks, there is a considerable overlap.

Volcanic, particularly lavas, may have high porosities and hence low densities. Generally, basic igneous rocks are heavier than acidic ones. Porosity, which affects the density of sediments so greatly, is of minor significance in most igneous and metamorphic rocks unless they are highly fractured. Density usually increases with the degree of metamorphism because the process tends to fill pore spaces and recrystallize the rocks in a denser form. Thus, metamorphosed sediments such as marble, slate, and quartzite generally are denser than the original limestone, shale and sandstone.

The same is true for the metamorphic forms of igneous rock, gneiss versus granite, amphibolite versus basalt, and so on. With few exceptions, non-metallic minerals have lower densities than the average of rocks. Metallic minerals, on the other hand, mainly are heavier than this average. Now gravity instruments. The absolute measurement of gravity is usually carried out at a fixed installation by the accurate timing of a swinging pendulum or of a falling weight.

Relative gravity measurements may be made in various ways. Three types of instruments, the torsion balance, the pendulum, the gravimeter. Absolute measurement of gravity. Although the timing of a freely falling body was first method of measuring, the accuracy was poor because of the difficulty in measuring small time intervals. The method has been revived as a result of instrumentation improvements and elaborate free fall installations are now located at several national laboratories. It is necessary to measure time to about 10^{-8}s and distance to less than 0.5 μm to obtain an accuracy of 1 mGal with a fall of 1 or 2 m. Until recently, the standard method for measuring gravity employed a modified form of the reversible Kater pendulum.

The value of gravity was obtained by timing a large number of oscillations. Relative measurement of gravity. The first is the portable pendulum. The pendulum has been used for both geodetic and prospecting purposes since g varies inversely as the square of the period T. Thus, if we can measure the periods at two stations to about one microsecond, the gravity difference is accurate to one milli Gal.

This is not difficult with precise clocks such as quartz crystals, cesium or rubidium. The pendulum has been used extensively for geodetic work, both on land and at sea. Portable pendulums used in oil exploration during the early nineteen thirty had a sensitivity of about zero point two five milli Gal. Pendulum apparatus was complex and bulky. Two pendulums swinging in opposite phase were used to reduce sway of the mounting; they were closed in an evacuated, thermostatically controlled chamber to eliminate pressure and temperature effects.

To get the required accuracy readings took about zero point five hour. Second is the Torsion Balance. A fairly complete account of the salient features of torsion balance can be found in Nettleton. Here you can see the schematic of the torsion balance in the figure. Two equal masses, m, are separated both horizontally and vertically by rigid bars, the assembly being supported by a torsion fiber with an attached mirror to measure rotation by the deflection of a light beam.

Two complete beam assemblies were used to reduce the effects of support sway. Readings were taken at three azimuth positions of the beam assemblies, normally one twenty degree apart to get sufficient data to calculate the required results. Elaborate precautions were required to minimize extraneous effects such as temperature and air convection. Each station had to be occupied for approximately one hour so that daily production was only eight to ten stations. The deflection of the torsion balance beam is due to horizontal and vertical changes in the gravity field resulting from curvature of the equipotential surfaces.

Now third is the stable type gravimeters. The first gravimeters dating from early nineteen thirties were of the stable type but these have now been superseded by more sensitive unstable meters. Nettleton describes a number of different gravimeters. All gravimeters are essentially extremely sensitive mechanical balance in which a mass is supported by a spring. Small changes in its gravity move the weight against the restoring force of the spring.

Whereas the displacement of the spring is small, Hooke's law applies, that is the change in force is proportional to the change in length. The period of oscillation of this system is capital T is equal to two pi capital M by K to the power half.

$$T = 2\pi(M/k)1/2$$

For good sensitivity, the period is very large and measurement of delta g requires considerable time. Stable gravimeters are extremely sensitive to other physical effects such as change in pressure, temperature and small magnetic and seismic variations. Fourth one is the unstable type gravimeters also known as labilized or astatized gravimeters.

These instruments have an additional negative restoring force operating against the restoring spring force that is in the same sense as gravity. The essentially are in a state of unstable equilibrium and this gives them greater sensitivity than stable meters. Their linear range is less than for stable gravimeters, so they are usually operated as null instruments. Thyssen gravimeter, although now obsolete, illustrates very clearly the astatic principle. The addition of the mass m above the pivot raises the center of gravity and produces the instability condition.

If g increases, the beam tilts to the right and the movement of m enhances the rotation; the converse is true for a decrease in gravity. At present, the Worden and LaCoste-Rogberg meters are the only types used for exploration. Fifth one is the Lacoste-Rogberg gravimeter. Lacoste-Romberg gravimeter was the first to employ a zero-length spring, now used by almost all gravimeters. A zero-length spring is one in which the tension is proportional to the actual length of the spring, that is, if all the external forces were removed, the spring would collapse to zero length.

The advantage of the zero length spring is that if it supports the beam and mass m in the horizontal position, it will support them in any position. Zero length springs are built with initial tension so that a threshold force is required before spring extension begins as with a door spring. In operation, this is a null instrument, a second spring being used which can be adjusted to restore the beam to the horizontal position. The sensitivity of gravimeters in use in surface exploration is generally zero point zero one milli Gal and the instrument requires a constant temperature environment, usually achieved by keeping it a constant temperature that is higher than the surroundings. Calibration of gravimeters. Both the Worden and Lacoste-Romberg meters are null instruments, and changes in gravity are shown as arbitrarily scale divisions on a micrometer dial.

There are several methods for converting these scale readings to gravity units. Theoretically, calibration can be carried out by tilting because a precise geometrical system is involved, but this is not the usual procedure. Generally readings are taken at two or more stations where values of gravity are already known. If the value of delta g between the stations is large enough to cover a reasonable function of the instrument range, a linear response is usually assumed between them. However, one should occupy several additional stations if possible.

Now applications of the gravity method. The gravity measurements could obviously be applied anywhere where sufficient density contrast is expected. Nevertheless, there are situations and field conditions suitable and unsuitable. Sometimes gravity excels is original geological mapping. It is due to the fact that gravity meter is easily portable, does not need any wires and cables and one or two people are enough to operate it.

Used in measuring long traverses. Another advantage is the high depth reach- It is common to model structures in the depth of several kilometers. Another field where the gravity measurements are indispensable is the mapping of voids, that is, cavities. There are not many geophysical methods that could directly detect voids. Therefore, the gravity method is often used to search caves, old mines and galleries or different voids and cavities beneath the roads.

The gravity methods are used chiefly for the exploration of oil and gas. These have been used successfully for outlining anticlines, buried ridges, igneous intrusions, faults, and other geological structures. The gravity survey has also been utilized for the exploration of metallic ore bodies such as massive sulfide ore, iron ore, and chromite ore. Very common application of gravity method is mapping of the sedimentary basins for the oil prospection. If the densities of sediments are known, then not only the lateral extent but also the depth of the basin could be mapped.

Another example from the oil X prospection is the mapping of salt domes since they often form oil and gas deposits. This set of examples could be finished by volcanoes which are often mapped using the gravity data. The eruption of the volcanoes is very forceful, the explosion creates a larger crater and shatters the country rock. After the explosion, part of the material falls back to the crater, however, is fluffed up by the explosion and hence its density is lower than used to be. Therefore, a gravity profile crossing the diatreme shows a distinct gravity low.

However, the best results are always obtained by combination of several geophysical methods. Now let us summarize the chapter. We have discussed first that introduction to geophysics. We have seen that geophysics is the study of Earth's physical properties and processes using physics-based methods to explore subsurface structures. Then we have discussed about the geophysical methods.

Various geophysical techniques such as gravity, magnetic, seismic, electrical methods are used to investigate Earth's interior. Then we have discussed the gravity methods. Gravity methods measure variation in Earth's gravitational field to infer subsurface density contrast, aiding geological exploration. For this, we have discussed the Newton's law of gravitation. This fundamental law states that every mass attracts each other, every mass attracts each every other mass with a force proportional to their masses and inversely proportional to the square of their distance. Acceleration of gravity refers to the rate at which the objects accelerate due to earth's gravitational pull approximately nine point eight one meter per second square at the surface.

Then we have discussed the densities of rock and minerals. Earth's gravity field is influenced by rocks and mineral densities with denser materials causing stronger gravitational anomalies. Then we have discussed gravity instrument that is gravimeters and other instruments measure tiny variation in gravitational acceleration to detect subsurface geological features. And lastly we have discussed the application of gravity method in which we have seen that gravity surveys are used in resource exploration, groundwater studies, and geotechnical investigations to map the subsurface features. Thank you very much to all.