

Index

- acceleration, 445
- active state of stress
 - in a bin, 69, 187, 190
 - in a hopper, 127, 133
- added mass force, 36
- adhesion, 16, 59
- aerated granular material, 40
- ageing, 17
- alternating tensor, 407
- alternative boundary condition for a free interface, 362
- angle
 - of dilation, 95, 111
 - of internal friction, 61, 65, 82
 - of repose, 1, 166
 - of stability, for a heap, 48
 - of wall friction, 59, 131
- angular
 - acceleration, 447
 - velocity, 24, 242
- angular momentum balance
 - for a continuum, 29, 34
 - for a spherical particle, 23
 - for a rigid body, 43
- anisotropic material, 62, 63
- anisotropy of the microstructure, 325
 - effect of, on the constitutive relations, 326
- arc length, 212, 421
- arching, 17, 112
- asperity, 18
- associated flow rule
 - for the extended von Mises yield condition, 241
 - for plane flow, 92, 100
 - for three-dimensional flow, 226
- asymptotic fields, for a hopper, 164, 205
- avalanche, 18
- axial segregation, 11
- axisymmetric hopper, 116
- balance law, 29
- ball mill, 26
- basis vector, 403
- Basset force, 36
- batch discharge
 - from a bin, 253, 254, 276
 - from a hopper, 51, 162
- Beverloo correlation, 117
- bin, 5
 - cylindrical, 253, 256
 - of rectangular cross section, 178
- body force, 33
- Boltzmann equation, 297
 - at $O(K)$, 314
 - at $O(\epsilon)$, 322
 - for rough particles, 379
 - for smooth particles, 299
- Boltzmann operator
 - linearized, 314
- Bond number, modified, 15, 42
- boundary conditions
 - alternative, at a free interface, 362
 - at a free interface, 355
 - for the frictional-kinetic model, 395, 396
 - from the high-density heuristic theory, 332
 - at the hopper exit, 129, 152
 - along a hopper wall, 134
 - from the kinetic theory, 332
 - for rapid flow, at solid walls, 331
- Brennen–Pearce solution, 134
- bulk
 - density, 19
 - solid, 1
- bulk viscosity in rapid flow, 320, 323, 389, 391
- bunker, 5
- buoyancy
 - for a single particle, 13
 - for a suspension, 39
- capillary force, 14
- Cartesian tensor notation, 407
- cellular automata, 28
- center of mass, 44
- centrifugal force, 448
- change of frame, 440, 443
- Chapman–Enskog expansion, 307, 309
- characteristic, 143, 420
 - equation, 64
- chute, 5, 26
 - smooth and rough, 352, 353

Index

- chute flow, 349
 - analysis using frictional-kinetic model, 396
 - analysis using high-density heuristic theory, 356
 - analysis using kinetic theory, 359
 - isotropic compression of, 222
 - experimental observations of, 351
- Clausius–Duhem inequality, 29, 92
- clay, 17, 76
 - compression and extension tests, 223, 224
 - isotropic compression of, 222
 - yield surface for, 110
- coaxiality condition
 - in cylindrical coordinates, 126
 - data related to, 88–90
 - for plane flow, 87
 - in spherical coordinates, 260
 - proof of, 434
- coefficient
 - of earth pressure at rest, 60, 69
 - of kinetic friction, 59, 72
 - of static friction, 58, 72
- coefficient of restitution, 288
 - occurrence of, in the constitutive relations, 323
 - for particle–wall collisions, 333, 334
- cofactor, 417
- cohesion, 16, 58, 61
- cohesionless material, 17, 240
- cohesive material, 16, 17, 244
- collisional contribution to, the stress, flux of
 - fluctuational energy. *See* streaming and collisional contribution
- column
 - matrix, 403
 - vector, 403
- compaction, 73
 - branch of the yield locus, 78
- compatibility condition, 186, 420–421
- compressible flow, 154, 203
- compression test, triaxial, 223
- condensation, of moisture, 18
- configuration, of a body, 30
- conical
 - hopper, 117
 - yield condition, 267
- conservation law, 430
- constitutive equation, 29
 - for an isotropic material, 435
- constitutive relations for rapid flow
 - in the high-density heuristic theory, 291
 - in the kinetic theory for rough particles, 389, 390
 - in the kinetic theory for smooth particles, 323
- contact
 - angle, 14
 - force, 16
 - between particles, 13
- continuity equation, 22
- continuum model, 22, 28
 - validity of, 28
- coordinate transformation
 - reflection, 438
 - rotation, 437
 - time-dependent, 440
 - time-independent, 435
 - translation, 435
- coordination number, 21
- core flow, 5, 122
- Coriolis
 - acceleration, 447
 - force, 448
- corotational
 - derivative, 234
 - frame, 234
- Cosserat continua, 380
- Couette cell, cylindrical, 54, 86, 246
- Coulomb
 - force, 13
 - yield condition, 61, 68, 108
- couple stress, 380
- creeping flow, 37, 49
- critical
 - damping, 51
 - voids ratio, 73
- critical state, 73
 - approximation, 125
 - curve, 74
 - line, 81
 - theory, 79
- cross
 - product, 407
 - section of a yield surface, 217
- cubical triaxial test, 225
- curl of a vector, 412
- current configuration, 30, 52
- cylindrical coordinates, 412
- damping coefficient, 25
- dashpot, 25, 50
- deep hopper, 129
- dense
 - random packing, 22
 - sample, 71, 74
- density
 - of the granular material, 21
- departure from equilibrium, 301
- determinant
 - of a matrix, 410
 - of a second-order tensor, 409
- deviator stress, 66
- deviatoric
 - normality, 229
 - stress tensor, 215
- difference scheme
 - Euler, 424
 - predictor-corrector, 425
 - second-order, 425
- differential
 - balances, 31
 - energy balance, 34
 - linear momentum balance, 33, 52
 - mass balance, 32, 52
- diffusion equation, 277
- dilatancy, 57
- dilation, 73
 - branch, 78
- dipole, 13

Index

- direct
 - collisions, 297
 - shear box, 70
- discontinuity
 - curve, for a bunker 193, 202
 - surface, for a hopper, 152
- discontinuous solution, 430
 - admissible, 432
 - for a bunker, 193, 197, 202
 - for a hopper, 152
- discrete
 - element method, 23
 - model, 22–23
 - model for a heap, 50
- displacement
 - gradient, 248
 - vector, 31, 248
- dissipation inequality, 92
- distinct element method, 23
- divergence
 - of a second-order tensor, 412
 - theorem, 44
- domain
 - of dependence, 186
 - of determinacy, 205
- dot product of two vectors, 405
- double
 - dot product, 408
 - shear apparatus, 89
 - shearing model, 101, 114
- drag force
 - exerted by a fluid, 37, 39, 52
 - exerted by a granular material, 87
- drained
 - angle of repose, 15, 42
 - test, triaxial, 222
- Drucker–Prager yield condition, 216
 - for a cohesive material, 244
- dry granular material, 1
- dummy index, 404
- dyadic product, 406
- effective stress, 222
- eigenvalue
 - of a differential equation, 141
 - of a matrix, 64, 109
- eigenvector, 64, 109
- elastic
 - collisions, 285
 - deformation, 76, 78
 - equations, 245
- elastic–viscoplastic equations, 214
- elastoplastic equations, 214
- electromagnetic force, 13
- electrostatic force, 13, 43
- emptying of a hopper, 51
- energy
 - balance, 34
 - flux vector, 34
 - transfer by conduction, 34
- entropy balance, 29
- envelope, of Mohr’s circles, 101, 111
- event-driven method, 28
- equation of equilibrium, 36
- equations of motion
 - for rough particles, 378, 381
 - for smooth particles, 305, 307
- equipartition of energy, 285, 383, 385
 - in granular mixtures, 327
- exit shock, for a hopper, 152, 164. *See also* free-fall curve
- extended
 - principal stress space, 80
 - Tresca yield condition, 218
 - von Mises yield condition, 216
- extension test, triaxial, 222
- failure, 72
- fan, of characteristics, 187
- flooding, 40
- flow
 - between horizontal plates, 85, 104, 229, 236, 339
- flow rule, 84
 - in cylindrical coordinates, 154
 - data related to, 228
 - for plane flow, 91, 100
 - for three-dimensional flow, 226
- fluctuational kinetic energy, 289
 - balance for nearly perfectly rough particles, 381
 - balance for smooth particles, 291, 307, 408
 - conductivity of, 292, 323, 390, 391
 - dissipation rate of, 292, 307, 323, 390, 391
 - flux of, 291, 307, 323
- fluid-particle
 - interaction, 36
 - suspension, 1, 38
- force
 - balance, 36
 - chain, 4
- Fourier transform, two-dimensional, 282
- frame indifference, 439
 - and constitutive equations, 233, 443
 - of fluctuational energy balance for rough particles, 381, 391
 - of Jaumann derivative of the stress, 445
 - of spin distribution, 387
 - of stress gradient, 447
 - of stress for nearly smooth particles, 391
 - of stress tensor, 442
 - of rate of deformation tensor, 445
- frame indifferent
 - scalar, 441
 - second-order tensor, 442
 - vector, 441
- free
 - index, 404
 - stream velocity, 36
- free-fall curve, for a hopper, 203. *See also* exit shock
- friction, 18, 26
 - wear-free, 19
- frictional stress
 - in frictional-kinetic model, 395
 - in viscometric flows, 397
- frictional-kinetic model, 395
 - application to chute flow, 396
 - boundary conditions for, 395, 396

Index

- fully developed flow
 - for the double-shearing model, 104
 - of a hypoelastic material, 236
 - in an inclined chute, 6
 - of a Lévy–Mises material, 86
 - of a Newtonian fluid, 85
 - of a rigid-plastic material, 229
- fully rough wall, 112, 133
- funnel flow
 - in a bunker, 5, 196
 - condition for, 196, 265, 268
 - in a hopper, 122, 265, 273
- Galilean transformation, 50
- γ -ray
 - attenuation, 75, 251
 - densitometer, 124
- Gaussian integrals, 453
- genuine solution, 430
- Goodman–Cowin equations, 214, 230
- gradient
 - operator, 411
 - plastic equations, 214
 - of a scalar, 411
 - of a vector, 411
- grain temperature, 289, 296
 - viscosity of, 327
- Granta-gravel, yield condition for, 216
- granular gas, 285
- granular jump, 353
- granular material, 1
- granular mixtures, 326
 - equipartition of energy in, 327
- Green's theorem, 430, 431
- H* theorem, 300
- Haar–von Karman hypothesis, 261
- Hamaker constant, 13
- heap, 1, 24, 41, 166
 - discrete model for, 50
- high-density heuristic theory for granular gases, 290
 - constitutive relations for, 291, 292
- hopper, 5
- hopper wall
 - rough, 131
 - shallow, 191, 195
 - smooth, 127
 - steep, 191
- hourglass, 2, 106
- Hvorslev surface, 75, 110
- hydraulic diameter, 119
- hydrodynamic equations. *See* equations of motion
- hydrodynamics variables
 - definition of, 305, 306
 - relaxation time of, 294
 - for rough particles, 378
- hyperbolic equations, 421
 - for a bin, 186
 - for a bunker, 196
 - for a hopper, 143, 203
- hypoelastic material, 235, 236, 247
- hypoplastic viscous model, 273
- hysteresis
 - in chute flow, 399
 - in isotropic compression, 222
 - loss, in rolling, 24
 - in uniaxial compression, 83
- inclined plane, 42, 107
- incompressible flow, 87, 96, 103
 - angle of dilation for, 111
 - in a hopper, 123
- index notation, 404
- inelastic collisions, 285
 - energy dissipation in, 289
 - model for, 288
- inelastic particles or grains, 286
- inelasticity parameter ϵ , 307
- inertia tensor, 44
- inertial term, 34
- integral
 - angular momentum balance, 47
 - balances, 31
 - linear momentum balance, 33
 - mass balance, 32, 52
- intermediate flow, in a bunker, 197
- internal energy balance, 34
- invariants of a tensor. *See* principal invariants
- inverse collisions, 297
- inverse collisions, precollision velocities
 - for rough particles, 379
 - for smooth particles, 298
- inverse of a tensor, 409
- irrecoverable deformation, 76
- isotropic
 - compression test, 222
 - loading, 247
 - material, 62, 435
 - tensor valued function, 243
- Jacobian, 52
- Jacobian
 - for change of phase space variables, 297
 - for transformation of $(\hat{\mathbf{C}}_1, \hat{\mathbf{C}})$ to $(\hat{\mathbf{g}}, \hat{\mathbf{G}})$, 299, 379
 - for transformation between direct and inverse collisions, 299, 379
- Janssen solution, 60, 184, 211
- Janssen–Walker solution, 210
- Jaumann derivative, 234
- Jenike shear cell, 70
- Jenike–Shield yield condition, 219
- jump balances, 428
 - for a bunker, 193
 - for a hopper, 152, 164
 - mass, 428
 - momentum, 429
- jump conditions
 - for conservation laws, 432
 - for linear hyperbolic equations, 432
- Kelvin modes, 368
- kinematic model, 276
- kinetic theory
 - for rough inelastic particles, 374
 - for smooth inelastic particles, 295

Index

- Knudsen number, 308
- Kronecker delta, 404
- laboratory frame, 30
- Lade–Duncan yield condition, 219
- Laplacian operator, 411
- layering modes, 368
- Lévy–Mises equations, 84, 266
- Lévy’s flow rule. *See* Lévy–Mises equations
- lift force, 36
- linear momentum balance
 - for a continuum, 29, 33
 - for a particle, 23
 - for a rigid body, 44
- linearized stability analysis
 - for the radial fields in a hopper, 141, 162
 - for rapid shear flow, 366
- liquid bridge, 14, 42
 - toroidal approximation for, 41
- load cell, 195, 256
- loading, 88, 222
 - path, 75
- local volume averaging, 38, 52
- loose
 - random packing, 22
 - sample, 71, 74
- major principal stress, 65
- mass
 - flow, 5, 122, 166
 - flow, criteria for, 196, 269
 - flux, 152
 - holdup, 6
- mass balance, 32
 - for the fluid phase, 38
 - for the particle phase, 38
- mass flow rate, for a hopper, 116, 129
 - correlation of Al-Din and Gunn, 162
 - correlation of Beverloo et al., 117
 - correlation of Rose–Tanaka–Beverloo–Nedderman, 119, 137, 263
 - from the Brennen–Pearce solution, 136
 - from the power series solution, 149
 - from the solution of Nguyen et al., 263
 - from the *SWRG* solution, 129, 262
- material
 - coordinates, 30
 - derivative, 31
 - frame indifference, 443
 - point, 30
 - volume, 30
- matrix, 406
 - representation of a tensor, 406
- maximal angle of stability, 48
- maximum
 - shear rate, 94
 - shear stress, 66
- Maxwell–Boltzmann distribution, 300
- Maxwell transport equation
 - for rough particles, 379
 - for smooth particles, 302
- mean curvature, 42
- mean free path, 290, 301
- mean free time, 295
- mean stress
 - in three dimensions, 215
 - in two dimensions, 66
- mechanical energy balance, 35, 307
- method
 - of characteristics, 185, 424
 - of moments, 316
- minor principal stress, 65
- modified Cam clay, yield condition for, 244
- Mohr–Coulomb approximation, 203
- Mohr–Coulomb yield condition, 65, 68, 219
- Mohr’s circle
 - for the rate of deformation tensor, 94, 112
 - for the stress tensor, 66, 68, 111
- molecular chaos, 299
 - with Enskog correction, 299
- moment of inertia, 24
 - for a sphere, 44, 376
- momentum balance
 - for the fluid phase, 38
 - for the particle phase, 38
- motion of a continuum, 30
- multiple steady states
 - in chute flow, 351
 - in standpipe flow, 11
- nearly perfectly rough particles, 378
 - constitutive relations for, 389
 - equations of motion for, 381
 - velocity distribution for, 382
- nearly smooth particles, 378
 - constitutive relations for, 390
 - equations of motion for, 381
 - velocity distribution for, 386
- neutral stability,
 - for plane Couette flow, 369
 - for the radial fields, 141
- Newtonian fluid, 37, 85
- nonassociated flow rule, 92, 229
- norm of a tensor, 235
- normal consolidation, 77
 - curve, 222
- normal stress differences, 310
- normality, 93
- normally consolidated sample, 77
- octahedral plane, 217
- oedometer, 82
- one-dimensional deformation
 - of a hypoelastic material, 236
 - of a rigid-plastic material, 230
- orthogonal
 - curvilinear coordinates, 412
 - matrix, 410
 - second-order tensor, 410
- packings, 21
- pair distribution function, 299
 - anisotropy of, 325
 - at contact, 300, 304
 - at equilibrium, 300

Index

- partially saturated granular material, 1
- particle
 - density, 19, 21
 - path, 231
- particulate solid, 1
- passive state of stress
 - in a bin, 69, 187
 - in a hopper, 127, 133, 190
- peculiar
 - spin, 378
 - velocity, 296
- perfectly rough particles, 375
- phase space, 295, 378
 - differential volume in, 297
- phase velocity, 369, 455
- photoelastic material, 4, 90
- Π -plane, 217
- plastic
 - deformation, 76, 77, 84, 91
 - potential, 91, 227
 - potential flow rule, 100
 - potential locus, 91
- plasticity theory, 82
- plane Couette flow, 339
 - analysis using high-density heuristic theory, 340
 - analysis using kinetic theory, 346
 - stability of, 369
- plane flow, 55
- plowing, 19, 62
- plug
 - flow, 6, 169, 256
 - formation in rapid flow, 348
- permutation symbol, 407, 416
- Poisson's ratio, 245, 246
- polar
 - elastoplastic equations, 214
 - hypoplastic equations, 214
 - molecule, 13
- pore pressure, 222
- porosity, 19
- position vector, 434
- powder, 1
- power series solution, 147
- Prakash–Rao yield condition, 156
- Prandtl–Reuss equations, 84
- pressure
 - of a fluid, 36, 86
 - rise in standpipe flow, 9
- principal invariants, 65, 109, 213
- principal stress, 64, 109
 - axis, 65, 109, 110
 - direction, 65
 - space, 214
- projection of a surface, 44
- product of two second-order tensors, 408
- pseudo
 - scalar, tensor, 456
 - vector, 384, 456
- pseudothermal energy, 289
 - balance for nearly perfectly rough particles, 381
 - balance for smooth particles, 291, 307, 408
 - conductivity of, in the high-density heuristic theory, 292
 - conductivity of, for nearly perfectly rough particles, 390
 - conductivity of, for nearly smooth particles, 391
 - conductivity of, for smooth particles, 323
 - dissipation rate of, 292, 307, 323
 - flux of, 291, 307, 323
- quasi-static flow, 41
- quasilinear system, 420
- radial segregation, 11
- radial stress field
 - for a conical hopper, 264, 267
 - for a wedge-shaped hopper, 138
- radial velocity field
 - for a conical hopper, 265, 268
 - for a wedge-shaped hopper, 139
- radio pill, 140, 259
- random packing, 22
- Rankine zone, in a bin, 187
- rapid flow, 54
- rate
 - dependent equation, 273
 - independent behavior, 62, 86
 - independent equation, 86
 - type material, 235
 - of working of the stresses, 34
- rate- and state-variable model, 132
- rate of deformation tensor, 37
 - components of, 83, 413, 415
 - defined in the compressive sense, 83
 - interpretation of the components of, 110
- reference
 - configuration, 30, 52
 - frame, 30
- regular packing, 21
- relative velocity, 37
- reloading, 82, 89
- Reynolds number, 37, 39
- Richardson–Zaki equation, 39, 52
- right-hand rule, 407
- right-handed system, 407
- rigid body
 - motion, 83
 - rotation, 242
- rigid-plastic material, 78, 84, 229, 230
- rolling friction torque, 24
- Roscoe surface, 77, 79, 110
- rotating cylinder, 11, 113
- rupture layer, 73
 - in a bunker, 56, 166, 200, 203
 - in a hopper, 122
 - in a soil specimen, 56
- rupture surface. *See* rupture layer
- sandpile, 1
- saturated granular material, 1
- scalar product
 - of second-order tensors, 408
 - of vectors, 405
- second
 - law of thermodynamics, 29
 - order tensor, 405

Index

- segregation, 2, 11
- series solution
 - for a conical hopper, 263
 - for a wedge-shaped hopper, 135, 147
- settling of a suspension, 39
- shear
 - box, 70, 71
 - between horizontal plates, 85, 104, 229, 236, 339
 - layer, 6
 - rate, 54
 - strain, 75
- shear band. *See* rupture layer
- shear viscosity in rapid flow, 319, 320, 323, 389, 391
- shearing deformation, 102
- shock, 432
- silo, 5
- simple shear apparatus, 73
- singlet distribution function, 296, 378
- slip plane, 68, 162
- slip velocity, 331
- slow flow, 54
- smooth particles, 285
 - collisional impulse for, 289
 - equations of motion for, 306
 - equilibrium distribution function for, 300
 - kinetic theory for, 295
 - Maxwell transport equation for, 302
- smooth wall, 61, 127
- smooth wall, radial gravity problem
 - compressible flow, 154
 - for a conical hopper, 262
 - for a wedge-shaped hopper, 125
- Sokolovskii variables, 66
- solid angle, 297
- solids fraction, 19
 - data for a bin, 251
 - data for chute flow, 355
 - data for a hopper, 122
- Sonine polynomials, 316
- space diagonal, 214
- specularity coefficient, 333, 338
- spherical
 - coordinates, 414
 - shell, deformation of, 245
- spin, 375
- spin tensor. *See* vorticity tensor
- spin viscosity, 391
- spring constant, 25
- spring–mass–dashpot system, 50
- stability
 - of the double-shearing model, 114
 - of plane Couette flow, 369
 - of the radial stress field, 141, 162
 - of the radial velocity field, 142
 - of a slope, 108
 - of unbounded shear flow, 366
- stagnant material, 5, 180
- standpipe, 6
- statics, 36
 - fluid, 36
 - granular, 36
 - heap, 48
 - hopper, 107, 162
 - slope, 108
- stick-slip, 180, 257
- stiffness, 25
- Stokes' law, 37
- stop–start operation, 259
- strain
 - engineering, 231
 - increment tensor, 83
 - natural, 231
 - tensor, 245, 413, 415
- streaming and collisional contribution to
 - the flux of fluctuational energy, 307, 310, 311, 320
 - the stress, 306, 310, 311, 319, 322
- streamline, 254
- stress
 - chain, 4
 - characteristic, 422
 - dilatancy, 96, 114
 - dip, 3
 - power, 35
 - tensor, 32, 419
 - vector, 32, 418
- stress tensor
 - for the fluid phase, 38
 - for the particle phase, 38
- substantial derivative, 31
- successive approximation procedure, for hopper
 - flow, 145
- summation convention, 404
- surcharge, 185
- surface tension, 14
- suspension, fluid-particle, 1
- symmetry
 - of the stress tensor, 34, 47
 - of yield surfaces, 80, 220
- tensile force, 17
- tensor, 405
 - first-order, 403
 - product, 406
 - second-order, 405
 - third-order, 407
- terminal velocity, 39
- test function, 430
- torque, 24, 246
 - variation with the shear rate, 86
- trace of a tensor, 406
- tracer particle, 250
- traction-free surface, 128, 136, 149
- transition region, in a bunker, 171, 183, 190
- translation of a sphere, 49
- transport theorem
 - generalized, 46
- transpose of a tensor, 409
- Tresca yield condition, 218
- triaxial test, 220
 - compression, 222
 - extension, 222
- turning point, 364
- two-particle distribution function, 296, 299

Index

- unconfined yield strength, 112
- undrained test, triaxial, 222
- uniaxial compression, 69, 82
- uniform shear, 286, 292, 348
 - of a mixture, 327
 - stability of, 366
- unit
 - tensor, 406
 - vector, 403
- unloading
 - isotropic compression, 222
 - uniaxial compression, 70, 82, 238
- van der Waals force, 13
 - for rough particles, 14
- vector, 403
 - product, 407
 - triple product, 416
- velocity
 - characteristic, 197, 426
 - discontinuity, 178, 197
 - gradient tensor, 35
 - of a material point, 30
 - weakening behavior, 86
- velocity data for a
 - bin, 178
 - conical hopper, 251
 - wedge-shaped hopper, 137
- velocity distribution function, 295
 - at equilibrium, for rough particles, 383
 - at equilibrium, for smooth particles, 300
 - for a pair of particles, 296
 - perturbation from equilibrium of, 309
 - at a wall, 334
- vertical channel, 6
- vibrated bed, 26
- virtual mass force, 36
- viscoelastic equations, 214
- viscometric flows, 310, 339
- viscoplastic equations, 214
- viscosity in rapid flow
 - of granular mixtures, 327
 - from the high-density heuristic theory, 292
 - from kinetic theory, 323, 389, 391
- voids
 - fraction, 19
 - ratio, 110
- volumetric strain, 82
- von Mises yield condition, 215
- vorticity, 242, 412
 - and angular velocity, 242
- vorticity tensor, 92, 241
 - components of
 - in cylindrical coordinates, 413
 - in spherical coordinates, 415
- wall
 - roughness, 131
 - yield condition, 59
- wall stress, data
 - after filling, bunker, 175, 177, 178, 180
 - dynamic, 178, 259
 - during flow, bin, 256–259
 - during flow, bunker, 177, 178, 180
 - during flow, hopper, 140
 - static, 178, 259
- wall stress oscillations
 - in bins, 256
 - in bunkers, 172, 177, 180
- walls
 - boundary conditions at, 331
 - as sources and sinks of energy, 345, 348
 - velocity distribution at, 334
- water content, 225
- weak solution, 430
- wedge-shaped hopper, 116
- wet granular material, 1
- yield
 - condition, 62
 - criterion, 62
 - function, 62
 - stress, in uniaxial tension or compression, 215
 - surface, 77, 79, 215
- yield locus, 78
 - convex, 93
 - in the σ – τ plane, 81, 111
 - in the N – T plane, 78, 111
- Young–Laplace equation, 42
- Young’s modulus, 26, 245
- zero extension line, 427